U.S. DEPARTMENT OF COMMERCE
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PB80-138571

Workshop on Atmospheric Dispersion Models in Complex Terrain

North American Weather Consultants, Goleta, CA

Prepared for

Environmental Sciences Research Lab, Research Triangle Park, NC

Nov 79

United States
Environmental Protection
Agency

Environmental Sciences Research
Laboratory
Research Triangle Park NC 27711

EPA-600/9-79-041
November 1979

PB80-138571

Research and Development

EPA

Workshop on Atmospheric Dispersion Models in Complex Terrain

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/9-79-041

2.

3. RECIPIENT'S ACCESSION NO.
PB 80 138571

4. TITLE AND SUBTITLE
WORKSHOP ON ATMOSPHERIC DISPERSION MODELS IN COMPLEX TERRAIN

5. REPORT DATE
November 1979

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NO.

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10. PROGRAM ELEMENT NO.
1AA603 AB-050 (FY-79)

11. CONTRACT/GRANT NO.
68-02-3223

12. SPONSORING AGENCY NAME AND ADDRESS
Environmental Sciences Research Laboratory - RTP, NC
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

13. TYPE OF REPORT AND PERIOD COVERED
Final 3/79 - 10/79

14. SPONSORING AGENCY CODE
EPA/600/09

15. SUPPLEMENTARY NOTES

16. ABSTRACT

During the period of July 16-20, 1979, an EPA-sponsored Workshop was conducted in Raleigh, North Carolina, to address problems associated with plume dispersion modeling in complex terrain. This Workshop was intended to aid in the design of a proposed EPA-funded research program dealing with this topic. Workshop participants represented a cross-section of environmental organizations, control agencies, industry and the scientific community with technical background and expertise in complex terrain modeling and field studies.

The Workshop was organized into five panels: Model Development and Analysis; Model Evaluation and Application; Experimental Design; Measurement Techniques; Data Management and Quality Assurance. This report contains the unabridged recommendations by each panel as summarized by the Panel Leaders. Also included are presentations by invited speakers who presented summaries of related complex terrain dispersion programs currently being sponsored by industry and by government agencies other than the EPA.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air pollution *Plumes *Atmospheric diffusion *Terrain *Mountains *Mathematical models *Meetings		13B 21B 04A 08F 12A 05B

18. DISTRIBUTION STATEMENT
RELEASE TO PUBLIC

19. SECURITY CLASS (This Report)
UNCLASSIFIED

20. SECURITY CLASS (This page)
UNCLASSIFIED

21. NO. OF PAGES
213

22. PRICE
A10 - A01

EPA Form 2220-1 (9-73)

EPA-600/9-79-041
November 1979

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PREFACE

During the period July 16-20, 1979, an EPA sponsored Workshop was conducted in Raleigh, North Carolina, to address problems associated with plume dispersion modeling in complex terrain. Similar topics have been the subject of other workshops sponsored during the past three years, such as the 1977 AMS Workshop on Stability Classification Schemes and Sigma Curves; the 1977 Specialists' Conference on the EPA Modeling Guideline; and the 1976 Albuquerque Workshop on Research Needs for Atmospheric Transport and Diffusion in Complex Terrain.

Since the Albuquerque Workshop the Clean Air Act Amendments of 1977 were signed into law. These amendments have placed a heavy burden upon regulatory agencies and industry in that they call for regulations which specify the use of dispersion models to achieve air quality limits pertinent to prevention of significant deterioration and attainment of National Air Quality Standards. The problem is particularly critical regarding dispersion in complex terrain since EPA, so far, has not specified models with demonstrated high degrees of reliability for use in refined modeling analysis in such settings. Furthermore, the need for these models continues to grow with the increasing demands for energy resource development in mountainous areas.

In response to this dilemma, EPA authorized the organization of this Workshop through the Meteorology and Assessment Division (MD) of the Environmental Sciences Research Laboratory (ESRL) at Research Triangle Park, North Carolina. The planning and coordination of the Workshop activities, and the preparation of this report, have been carried out by North American Weather Consultants (NAWC) under contract to EPA, with significant assistance from the Meteorology and Assessment Division.

The Workshop was organized into five panels on the following topics: Model Development and Analysis; Model Evaluation and Application; Experimental Design; Measurement Techniques; Data Management and Quality Assurance. The number of Workshop participants totaled 59. Of these, 47 were invited specifically to serve on the Workshop panels. They represented a cross-section of environmental organizations, control agencies, industry and the scientific community with technical background and expertise in complex terrain modeling and field studies. The other attendees were invited speakers, guests, and personnel from the Contractor and EPA contracting offices.

The Workshop agenda included four days of alternating plenary and work sessions. The opening plenary session began with presentations by invited speakers who presented summaries of related complex terrain dispersion programs currently being sponsored by industry and by government agencies other than EPA. This plenary session also included opening statements by EPA on their anticipated future programs and presentations by each Panel Leader on the goals of the Workshop and the tasks that the panel would attempt to accomplish over the next four days.

At the end of the Workshop these accomplished tasks were presented orally during the last plenary session in the form of recommendations by each panel how EPA should best proceed with the complex terrain program. The Panel Leaders handled the tasks of assembling the written statements from their respective panels and presented edited material to the contractor for publication following review by the panel members. These statements are published, unabridged, in this report together with summaries of stimulating discussions which took place during the other plenary sessions.

ABSTRACT

A Workshop, sponsored by the Environmental Protection Agency's Environmental Sciences Research Laboratory (EPA/ESRL), Meteorology and Assessment Division (MD), was held in Raleigh, North Carolina, during July 16-20, 1979. The goals of this conference were to focus on complex terrain modeling problems, and to develop recommendations to EPA with respect to design of a workable multi-year program to start in Fiscal Year 1980. Personnel from the Meteorology and Assessment Division (MD) of EPA provided "strawman" material for discussion at the conference. Based on this material, the conferees agreed that considerable benefit would be derived by focusing the conference on impingement problems.

Invited experts on various aspects of field studies, model development, model evaluation, and data management prepared recommendations and technical support documents on these topics and related budgetary allocations. The participants addressed in considerable detail questions on how to collect a representative data base to develop credible models for regulatory applications that would adequately handle plume impingement problems in elevated terrain.

The Workshop participants agreed in principle that EPA should adopt a two-phased field program approach, starting with a controlled experiment on a small, isolated hill of simple geometric setting, and then proceeding with a large scale program of increased complexity. It was also recommended that the modeling development program follow multiple development phases. The initial effort should be oriented towards improvements in Gaussian-based models, while the final effort should be aimed towards new model development incorporating complex flow fields in rough terrain with either Gaussian-based or "K theory" based models. Physical modeling programs should be an integral part of the above efforts.

The Workshop recommendations address the need for improved model evaluation techniques, statistical analysis methods, sensitivity analysis, comparative field data analysis, and independent evaluation techniques. Furthermore, informative recommendations were provided on problems concerning data management and quality assurance, as well as on specific costs relative to experimental design with suggested budgetary allocations for future programs.

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ACKNOWLEDGMENTS

More than 50 individuals were involved in the Workshop proceedings presented in this report. The contributions from this group, and in particular the unstinting efforts of the panel members can best be described as exemplary. Several participants in the Workshop deserve special acknowledgement, as indicated below.

Advance planning, assistance in selection of panel members, and preparation of "strawman" pre-conference documents by Mr. Lawrence E. Niemeyer, Mr. George C. Holzworth, Dr. William H. Snyder, and Dr. Robert G. Lamb of the Meteorology and Assessment Division of EPA at Research Triangle Park, are acknowledged with gratitude.

The five Panel Leaders, under whose guidance and motivation the Panels functioned, were notably effective in synthesizing large quantities of complex technical material into coherent panel reports. These Panel Leaders are: Dr. Bruce A. Egan (ERT), Mr. Roy Evans (EPA), Dr. Ronald E. Ruff (SRI International), Mr. Maynard E. Smith (MES), and Mr. Gene Start (NOAA-ERL).

Valuable background information was provided by special presentations made by invited speakers who summarized the related complex terrain programs currently sponsored by industry and by government agencies other than EPA. These speakers were: Dr. Glenn R. Hilst, Electric Power Research Institute; Dr. David S. Ballantine, Department of Energy; and Dr. Vernon Derr, National Oceanic and Atmospheric Administration.

SECTION 1

INTRODUCTION

At the request of EPA a Workshop was held in Raleigh, North Carolina, during July 16-20, 1979, to tackle the pressing problems associated with the development of improved mathematical models for predicting plume dispersion in complex terrain. Invited experts, with broad technical and scientific backgrounds, were assigned the tasks of generating recommendations and guidance to EPA for use in the planning of dispersion model development and associated field experiment programs over the next 3-5 years.

The manner in which the Workshop was organized, with five panels on topics essential to achieving the goals of the conference, is described in Section 3, Workshop Organization. The Workshop schedule allowed for periodic interchange of technical information through frequent plenary sessions.

Brief summaries of opening statements, presentations by invited guest speakers, and highlights of the technical discussions, which took place during these sessions, are presented in Section 4, Plenary Sessions.

Under the able leadership and direction of five invited panel leaders, the panels addressed a number of technical aspects of future EPA programs, as viewed from their respective specialties. Not only did the panels prepare these written recommendations under a very limited time frame, but the participants also prepared highly technical reports which the panel leaders arranged into comprehensive support documents to their panels' recommendations. These statements and recommendations are presented unabridged in Section 5, Panel Recommendations, in the format presented to the contractor by the Panel Leaders. The proceedings also include some excellent "strawman" scenarios prepared by EPA and distributed prior to or at the opening day of the Workshop. The scenarios served the stated purpose of introducing the participant to some of EPA's internal thoughts on suitable approaches to the problems at hand. They also served to quickly focus the panels' attention on critical concepts which needed to be examined in an open forum before the formulation of their recommendations. The "strawman" plans and other material and information distributed to the participants prior to the Workshop, are presented in Appendices A and B.

The Workshop proceedings have also provided a forum for additional comments by participants generated during their review of the final panel recommendations subsequent to the Workshop. These letters and comments are summarized in Appendix C.

Finally, it was recognized that the Workshop could only accomodate a limited number of invited participants, and that there were many highly qualified experts in the disciplines relevant to the Workshop topics who could not participate in person. Invitations were distributed to over fifty experts outside those attending the Workshop, providing an opportunity for them to submit ideas and topics for panel considerations. Several excellent technical inputs were received and utilized by the Workshop panels and recognition of these contributions is acknowledged in the list of participants.

SECTION 2

CONCLUSIONS

The Workshop provided a timely forum for technical discussions on topics pertaining to plume dispersion in complex terrain. The discussions covered a wide range of subject matters dealing with field study designs, data handling, and measurement techniques relevant to the tasks of model development and evaluations. The EPA "strawman" plans, which were prepared for consideration by the Workshop participants, provided an effective means of focusing the panels' attention on specific approaches to future EPA field studies and model development programs.

The panel recommendations and associated technical discussions clearly demonstrate the complexity of the problems, and that there are no simple solutions. There was general agreement on the overall approach regarding model development programs. This agreement was based on acceptance by the conferees of the concepts presented by EPA in their "strawman" documents (Appendix A) which recommended focusing on plume impingement for the initial effort. However, divergent viewpoints were frequently expressed by individual participants, and at times by panel leaders, regarding the details of the required experimental studies that would be most appropriate within the stated program constraints.

The wealth of technical information and panel recommendations generated by the Workshop relative to the specific goals expressed by EPA at the opening plenary session have been examined by the Workshop coordinators (NAWC staff), and the following seven conclusions were drawn.

1. THE OVERALL PLAN

All panels agreed in principle with an approach to model development starting with a controlled experiment on a small isolated hill of simple geometric setting. Once an initial understanding of plume impaction with elevated terrain is achieved, larger scale experiments should be conducted, and should include systematic investigation of phenomena with increased complexity. General agreement was also expressed on the need for a closely coordinated model development program, including the use of physical modeling techniques, to accompany the field studies. The total EPA program should be designed to facilitate coordination with other related efforts, such as the EPRI, DOE, and NOAA programs.

A lack of concensus emerged on the question of what physical hill size would be preferable for the small-scale program. Whereas the modeling panels considered a 100 m hill to be a desirable size for simple field experiments on non-buoyant tracer plume impaction, the panels on experimental design and measurement techniques expressed, during the plenary sessions, a preference for a medium size hill of 400-500 m. However, their written recommendations presented herein are in the form of pro and con assessments with respect to different field program scenarios, such as small scale (100 m hill), medium scale (400-500 m hill), and full scale (real plant) experiments in order to provide EPA with maximum guidance for reaching a final decision on this issue. The overriding concerns in this decision-making process must be that the scale of experiments can be extended to "real world" situations, and they must be consistent with the ability to measure the required parameters.

2. MODEL DEVELOPMENT APPROACH AND IMPLEMENTATION

There was general agrement on the recommended approach that the initial model development effort should be oriented towards reasonable "fix-up" to Gaussian-based models currently used in the regulatory practice. The subsequent model development activities should concentrate on developing and using better descriptions of the flow fields expected in rough terrain for a variety of meteorological and topographic settings. The resultant flow field descriptions could be used with either Gaussian-based models or with "K theory" based models.

3. MODEL TESTING AND DEMONSTRATION OF CREDIBILITY

There was general agreement on several recommendations stating the need for adequate model testing and evaluations. These procedures should include examination of model performance based on observed versus predicted comparisons. Emphasis was placed on the need for having model development data to meet requirements of model evaluation with adequate measurements to verify model performance. The recommendations also included the need to define the applicability of the result. Furthermore, the demonstration of credibility would be greatly improved by the use of flow visualization. This technique enhances understanding of the basic processes occurring during plume interaction with the terrain, which cannot be readily described from ground measurements of tracer concentrations alone.

4. MODEL APPLICATION IN NEW SETTINGS

The discussion of model transferability to other sites centered around the results to be obtained from the small scale versus large scale field programs. It was agreed that the basic process of plume impaction in simple, small scale experiments should be readily transferable to other settings. However, the more complex physical processes associated with large scale terrain features, such as complex plume trajectories, thermally induced mountain slope flows, and vertical wind shear, are so site specific as to make the transfer of results to new settings very difficult. Again the flow visualization techniques will greatly aid in the acceptance of transferability of the model.

Specific recommendations regarding model applications include the need for thorough documentation of the experiments, the data, and the model development. It is essential that, to assure proper use of the models, the documentation must include a list of limitations, special conditions, and confidence bands for future model applications.

5. THE SCIENTIFIC FEASIBILITIES OF PROPOSED FIELD AND LABORATORY STUDIES

The discussions on small versus medium and full scale experiments raised many questions on similarities in plume behavior. Doubts were expressed by some whether the surface boundary layer and vertical atmospheric structure associated with the small scale study would be applicable to "the real world". Since turbulent motion is very important in the plume impaction processes with elevated terrain, questions were also raised whether these processes can be simulated on a scale significantly different from that found in large scale complex settings. Other questions were concerned with plume impaction; whether it is dominated by surface induced turbulence or by turbulence at plume elevation. If the former persists, the size of the hill doesn't matter, but if the latter dominates, then the small hill experiment might be inappropriate.

The technical information and discussions generated by each panel, and presented in these proceedings are highly illuminating since they address these questions from different technical and scientific viewpoints. Recommendations were made that field programs should allow for testing the effects of scale, and that the impaction problem be studied as a function of terrain and meteorology. There was general agreement on the recommendation that physical modeling techniques be incorporated into the model development program. The applications and limitations of this technique must be defined.

6. EFFICIENT MEANS OF DATA HANDLING

The primary inputs on data handling were given by the Data Management and Quality Assurance Panel. The recommendations from this panel provide an informative overview of major phases of data management and information feedback as a quality control measure. They suggest that, following implementation of a Data Acquisition Plan, the following three actions should occur: 1) Field operations should provide for field data through an acquisition phase with quality assurance feedback; 2) data compilation processes should follow field data review and bring the data into a final check phase, again with quality assurance feedback; and 3) an independent data review should follow after preparation and delivery of reports to be accompanied by final quality assurance feedback. Although field activities are distinguished from off-site activities, this panel recommended that the same groups conduct these activities through the final data archiving process.

7. BUDGET ALLOCATIONS

The recommendations prepared by the panels dealing with field experimental design, instrumentation, and data handling contain a number of cost estimates and budgetary allocations. These estimates must be viewed relative to EPA's expected budgetary constraints of about $2.0 million per year for three years. The Measurement Techniques Panel presented specific cost estimates for the 100 m hill and larger scale projects as follows: For the 100 m hill, hardware costs alone were estimated to be near $2.6 million and the operation of the ground-based instruments could be around $40,000-$50,000 per month. Estimates for gaseous tracers, sampling equipment, laboratory analysis, towers without equipment, and plume visualization equipment are also included. For the larger scale experiments, hardware costs for Doppler Acoustic Systems could be around $40,000-$50,000, aircraft tracer measurements about $8,000 per day, lidar costs about $50,000 per month, and airborne lidar with ground based data systems about $4,000 per day.

The Experimental Design Panel prepared a budget estimate for 50 days of sampling during two 40-day research periods with continuous 18 months monitoring (without centralized data logging equipment) on a 400 m hill in the Western U.S. The cost estimate was nearly $2.9 million dollars based on direct costs and labor with a moderate contractor's charges (General and Administrative expense, and fee or profit).

The Data Management and Quality Assurance Panel submitted cost figures based on upper-bound requirements for two field study periods. The two-phased program would require approximately 12-13 person years. Personnel and support costs would consume about one million dollars, and field data facilities about $130,000. The estimated costs were considered consistent with the following budgetary allocation suggested by the Measurement Techniques Panel during panel session discussions: management (10%); field work and initial data processing (55%), data analysis and quality assurance (15%), and model development (20%). These proposed allocations were not discussed in depth during the Workshop.

SECTION 3

WORKSHOP ORGANIZATION

On March 9, 1979, North American Weather Consultants (NAWC) was authorized by the Environmental Protection Agency (EPA) to organize and conduct a Workshop to Develop Recommendations on Atmospheric Dispersion Models in Complex Terrain. The contract award was originally based on a task requiring NAWC to organize "a Workshop of invited experts on atmospheric transport and diffusion over complex terrain who will make specific recommendations for multi-year Government research that will significantly improve the reliability of practical mathematical dispersion models over complex terrain". Furthermore, the original plan specified two types of emission configurations: "1) Tall chimneys such as exist at fossil-fueled power plants and smelters and 2) assemblages of emitters relatively near ground level such as are expected in connection with oil shale resources development".

During the first planning meeting between the EPA contracting office and the contractor (NAWC) in Research Triangle Park, NC, on March 26-29, 1979, the overall Workshop effort was modified to address specifically the problem of plume dispersion from large fossil-fuel power plants in complex terrain. Agreement was also reached on the Workshop structure with plans to have five panels on the following topics: Model Development and Analysis, Model Evaluation and Application, Experimental Design, Measurement Techniques, and Data Management and Quality Assurance.

At the same meeting a list of potential participants was developed to include experts in applied and theoretical modeling, physical (laboratory-scale) modeling, field (full-scale) experimentation, instrumentation, data archiving, and quality control. Consideration was also given to obtaining a balance between the panel members' professional background with representation from federal and state agencies, universities, the electric power industry, and the private consulting industry. Finally, the assignment of the 47 participants to specific panels was made in such a manner as to provide some mixture of expertise, where possible, on each panel.

A pre-conference meeting, scheduled at the EPA facility in Research Triangle Park on June 6, was attended by the five panel leaders (or their substitutes) and the contractor. By this time, Raleigh, NC, had been selected as the site for the Workshop, following considerations of the cost and convenience of several other locations. The meeting covered technical apects of the Workshop, the respective roles of the panels, and final recommendations for the list of invited participants.

Subsequently, NAWC and EPA representatives prepared and distributed pre-Workshop material to panel leaders and members. These documents are included as part of the Workshop report. Invitations were also sent to over 50 experts in the fields listed above who could not be included in person at the Workshop, but who were given the opportunity to contribute construcive ideas and concerns to the panels for their deliberations. Those who responded to this special invitation with material for discussion are included in the list of participants.

The Workshop schedule (Figure 1) was designed to provide maximum interaction and exchange of information between the panels through alternating panel sessions and plenary meetings. The opening plenary session provided the opportunity for representatives from EPRI, DOE, NOAA, and EPA to present to the participants various programs which are currently planned or under way by their respective agencies on topics dealing with dispersion in complex terrain.

The recommendations prepared by each panel during the Workshop were presented to the participants during the final plenary session. Draft copies of the statements were distributed the following week to the respective panel members for final review. These statements represent the panel recommendations to EPA and are presented without editing by the contractor, as agreed during the conference.

EPA WORKSHOP SCHEDULE

JULY 16-20, 1979

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
8:30	REGISTRATION	PANEL MEETINGS	PANEL MEETINGS	PANEL MEETINGS	PANEL LEADERS MEETING
10:00		COFFEE	COFFEE	COFFEE	
10:30		PANEL MEETINGS	PANEL MEETINGS	PANEL MEETINGS	
12:00		BREAK	BREAK	BREAK	
12:30		LUNCH*	LUNCH*	LUNCH*	
1:00	PLENARY SESSION	PLENARY MEETING	PLENARY MEETING	FINAL PLENARY MEETING	
3:00	COFFEE	COFFEE	COFFEE	PANEL LEADERS MEETING	
3:15	PLENARY SESSION	PANEL MEETINGS	PANEL MEETINGS		
4:00					
4:30	INITIAL PANEL MEETINGS	BREAK	BREAK		
5:30	BREAK		PANEL LEADERS MEETING		
6:00	CASH BAR				
7:00	DINNER*	PANEL LEADERS MEETING	PANEL MEETINGS		
10:00					

*ARRANGED TO FACILITATE THE CONDUCT OF THE WORKSHOP.

Figure 1. EPA Workshop schedule.

SECTION 4

PLENARY SESSIONS

The plenary sessions were arranged throughout the Workshop to serve as a forum for exchange of information, as a means to stimulate discussions, and as a catalyst for the individual panels to achieve the primary goal of the conference, namely, to develop constructive guidance and recommendations for EPA. Section 4 summarizes the highlights of these sessions, starting with the opening plenary session and later focusing the attention upon major topics under discussion during subsequent sessions.

The first session was devoted partly to the opening statements by EPA, EPRI, DOE, NOAA and the contractor (NAWC). A brief summary of these statements in order of presentation is given below. During the second half of the first session, each panel leader presented opening remarks describing the tasks and the goals of their respective panels. A brief synopsis, with a list of the main topics for discussion by each panel, follows.

The third portion of this section deals with questions and issues that were generated by the panel leaders' progress reports during the subsequent plenary sessions. The "strawman" plans developed by EPA served the purpose of immediately focusing the participants' attention upon specific issues. The material presented herein shows these issues to be primarily the scale of future field studies relative to parameters to be measured, considerations in experimental design and data management, measurement techniques, and cost factors.

1. OPENING STATEMENTS

1.1 Summary of Opening Remarks by L. E. Niemeyer, Environmental Protection Agency

Considerations of complex terrain modeling problems were pioneered in the early 1940's by Hewson and Gill and reached a new prominence a few years ago when NOAA and the predecessors of DOE and EPA conducted the Southwest Energy Study. Other efforts have included a recent complex terrain study funded by the EPA and contracted by Geomet, Inc., and the Albuquerque Workshop organized by DOE three years ago. Standard Gaussian models have been adopted, but the improvement of the models has been difficult without the necessary funding for a comprehensive evaluation program. However, in light of the recent emphasis on oil shale and coal resource development in the West, EPA management has earmarked approximately $2.0 million per year for three years in order to make a significant impact on the problem of modeling plumes from large sources in mountainous terrain.

In a strawman approach prepared for the Workshop, EPA has suggested three main directions for studying the modeling problems:

1) A small hill study to focus on the key question of plume impingement,

2) A full scale study to verify the resulting plume impingement module developed under the small scale study,

3) Other aspects of the modeling problem such as plume transport, frequency of plume impaction for comparison with the standards, and turbulence or dispersion statistics.

The goal of the Workshop is to provide recommendations for a workable program considering EPA ideas but extending and revising them based upon the experience and background of the participants.

1.2 Summary of Opening Remarks by Einar L. Hovind, North American Weather Consultants

The planning and organization of this conference have been underway since March 1979 when EPA formally awarded North American Weather Consultants (NAWC) the contract to conduct this Workshop. EPA and NAWC agreed that the best way to achieve the stated purpose, namely to develop recommendations to EPA on the problem of plume dispersion from large fossil fueled power plants in complex terrain, was to arrange a five-panel Workshop with about 47 experts on the following panel topics: Model Development and Analysis, Model Evaluation and Applications, Experimental Design, Measurement Techniques, and Data Management and Quality Assurance.

The Workshop schedule consists of a mixture of plenary sessions and panel meetings, starting with this opening plenary session where representatives from EPRI, DOE, and NOAA will provide information on proposed and ongoing research programs conducted by the electric power industry and by government agencies other than EPA. It is felt that this information is highly relevant to the tasks placed upon each panel of this Workshop.

These tasks will be outlined later in this session by each panel leader. They will follow a presentation by the EPA Project Officer on the Workshop Goals, and the manner in which EPA expects to utilize the results of this Workshop in the planning of future field programs and modeling efforts on dispersion in complex terrain.

1.3 Summary of Related EPRI Research Programs by Glenn R. Hilst, Electric Power Research Institute

EPRI projects that are directly involved with complex terrain problems are organized under two main programs. The first is called the Air Quality Studies program and has two primary features. One is concerned with regional air quality studies of long range transport and multiple source effects. The major problems considered under this program have to do with fine particles and their chemical speciation, source attribution, and effect on visibility. A network of air quality stations is being instituted in the western region for gathering information on these problems. The second part of the Air Quality Studies is the Sulfate Regional experiment which is now in the analysis and modeling phase of its definition of SO_2-sulfate relationships.

The second major program, which is more related to individual plume behavior, is called the Plume Model Validation Project. The primary goal is the collection of substantial experimental data for the purposes of validating models for their general applicability and validating individual predictive modules, such as plume rise, transport, diffusive mixing, etc. Toward this end field projects are being organized to study plume behavior in progressively more complex situations, beginning with a plains site, a coastal site, and then finally, a complex terrain site. It is expected that more model development will take place with the complex terrain data base, because knowledge of plume behavior in these situations is limited.

In general, it should be recognized that any program dealing with complex terrain questions is going to be extremely expensive, and that the investment will have to be proved worthwhile. Nonetheless, decisions must be made on what is necessary to answer these questions irrespective of the cost. Certainly one way to maximize the benefit gained from the various research efforts is to promote coordination and cooperation among the interested parties so that the total of what is learned is more than the sum of the parts.

1.4 Summary of Related DOE Research Programs by David S. Ballantine, Department of Energy

DOE conducted a Workshop in Albuquerque in 1976 to address the poor state of knowledge of transport and dispersion in complex terrain. The Workshop outlined a recommended national effort at a level of about $30M over a five year period. It included a discussion of the need to study various complex terrain features and characteristic meteorological systems.

When new funding did not materialize, DOE redirected ongoing research efforts in the atmospheric sciences and in 1978 began a complex terrain program in the Geysers geothermal area of California. The Geysers area represented a site of opportunity where there was large scale energy development and where considerable data on meteorology and air quality had been collected because of environmental concerns. The focus in Geysers is on a study of nocturnal drainage winds.

Dr. Marvin Dickerson of LLL was selected as Project Director for the DOE Atmospheric Studies in Complex Terrain program which bears the acronym ASCOT. An initial two week field study was conducted in late July 1979 with participation by LLL, LASL, ATDL, PNL, WPL/NOAA, and a local contractor ES&S (Environmental System and Services). A major field experiment will be conducted in September 1980.

A preliminary critical review of complex terrain models was conducted by the ASCOT modeling group, which resulted in a recommended model development program which includes various statistical, dynamic, and physical modeling alternatives.

A longer range program is evolving for efforts beyond 1981 when the Geysers study should be completed. Various options based on considerations of different terrain features, meteorological phenomena, and relevance to DOE energy development programs are being examined.

1.5 Summary of Related NOAA Programs by Vernon Derr, National Oceanic and Atmospheric Administration

The responsibility of NOAA, and particulary the Environmental Research Laboratory, in this Workshop, is to aid in assessing the role of remote sensors and other sensors (such as aircraft instrumentation) that NOAA operates or that come from other sources. The main objective is to design and perform experiments to provide a widely applicable data set, which is acquired with a minimum of measurements and against which we can test models. In order to do this, several questions must be answered regarding such things as the representativeness of the data, the resolution in time and space, and the continuity of measurements required. It is also necessary to determine the basic set of weather conditions most concerned with impact, and how to describe these conditions at different scales. Another question to be addressed is the optimum configuration of remote sensing equipment.

Remote sensing equipment includes a wide variety of techniques and measurement capabilities, some of which are briefly described below.

1) A three-wave length lidar system (.347, .694, and 10.6 m) with polarization capabilities to identify and trace particulate pollutants

2) A new doppler-lidar system for measuring winds in clean air

3) Laser to measure wind or detect particulates

4) Microwave radiometric devices for measuring temperature, and humidity profiles, and liquid water content

There are two needs for sensors in this kind of a program. One to determine the prevailing meteorological conditions, and the other is to determine the actual paths of the particulates or gases. For these needs a combination of in situ, aircraft, and remote sensors is required.

1.6 Summary of Workshop Goals by George C. Holzworth, Project Officer, Environmental Protection Agency

EPA has decided that its initial effort in its complex terrain modeling program should focus on the problem of terrain impaction because this has been a source of controversy for both the regulatory agencies and the power industry, and because it is felt a significant impact can be made on this topic within available resources. More specifically, the problem has to do with a plume in a stable atmosphere encountering one or more terrain obstacles and particularly the first obstacle.

The primary goal of the study will be to generate significant results as soon as possible to demonstrate what can be done with the funds available. By significant results we mean the development of models with a demonstrated higher degree of reliability than current models in general use. These models must be reasonable and practical in terms of requirements for computing facilities, meteorological input and plant operations data. However, one way to effectively improve the modeling results is to specify more representative input information than is currently required.

The study plans envision the development of stable impaction models through a series of experiments on different scales, ranging from physical modeling to full scale field studies, which are linked together to demonstrate their credibility.

The strawmen proposed by EPA (Appendix A) are suggestions for the direction of this work. The goals of the Workshop are to make recommendations on the following aspects of the study:

1) The overall plan

2) Model development approach and implementation

3) Model testing and demonstration of credibility

4) Model applications in new settings

5) The scientific feasibilities of proposed field and laboratory studies

6) Efficient means of data handling

7) Budget allocations

In summary, the Workshop is designed to solicit scientific recommendations on how to most effectively and efficiently impact the problem of mathematically modeling dispersion over complex terrain and to do so with available resources.

2. PANEL LEADERS' DISCUSSION

The following outline is a synopsis of the major ideas presented in the first plenary session by each panel leader while addressing complex terrain issues in general and the scope of the proposed study in particular.

2.1 Dr. Bruce A. Egan - Model Development and Analysis Panel

A. Some of the problem areas associated with complex terrain situations that might be addressed are:

1) Regulatory issues (prediction of 3 and 24-hour worst cases).

2) Good Engineering Practice issues.

3) Near-surface releases.

4) Long distance transport.

5) Low level sources in a constraining valley situation.

B. The following are constraints on the scenario developed in the Workshop:

1) Want a model developed that will be useful in regulatory applications for complex terrain settings.

2) Need meaningful results on a timely schedule to assure future funding.

3) Program must have a high probability of success which precludes some approaches which may not contribute to regulatory applications.

4) The approaches should complement related efforts.

5) The end products should be able to serve as a basis for future efforts.

C. Within the constraints discussed, some directions are suggested:

1) Concentrate on a few high priority parameterization problems (such as the impact of a nearby elevated source).

2) Emphasize the simple models such as the Gaussian models, but collect data that would be more generally useful for other models.

3) Relate the simple field study and physical modeling and establish uses and limitations for the physical modeling.

4) Define the flow field and distortion effects, gradients of turbulence levels, and trajectories for specific source locations.

5) Separate the flow field model development and the dispersion model development.

D. Questions and Discussions from the Floor are briefly summarized below:

1) What averaging times are necessary to define the flow field? Something considered consistent with the scale of the problem which implies 5-20 min in the case of Snyder's strawman.

2) In reference to the point about separating the flow field and dispersion models, software has already been developed for treating the problem in this way.

2.2 Mr. Maynard E. Smith - Model Evaluation and Applications Panel

A. Considerations of various aspects of the planned study are discussed below:

1) The focus should be on limited experiments which would provide maximum information. In other words, the study shouldn't become so elaborate that one part of the program has to be sacrificed for another.

2) It is desirable to know to what extent wind tunnel modeling can be relied on, and so comparing this technique with the small scale study is appropriate. However, this is not likely to be the case in the large scale study due to the additional complexities of the situation.

3) Input data requirements must be simplified as much as possible in order that data be effectively acquired under actual field situations. This means data must be obtainable in reasonable time periods and with reasonable instrumentation.

4) A panel of expert review may be valuable.

5) The budget should include funds for evaluating and comparing the model with other field data.

6) It is important to consider and define how the model ought not to be used, as well as how it should be.

B. Comments from the Floor:

1) In response to the comments on wind tunnel modeling it was pointed out that progress has been made in modeling drainage and convective transport. However, this kind of modeling

may not be widely available to users involved in the regulatory process, and could not therefore be reasonably required in that process.

2.3 Mr. Gene Start - Experimental Design Panel

A. The design of the experiment depends on answers to some of the following questions:

1) What is the goal from the modeling standpoint? Are we trying to test and discriminate alternate theories? Which models should be considered?

2) What scale should be used - Lagrangian, Eulerian, or both?

3) What aspects of the problem should be emphasized - plume rise, impaction, etc?

4) How should the problem be approached? This question relates to what measurements should be taken and what scale and resolution are most appropriate.

B. Comments from the Floor:

1) The point was raised that it is important to design the study so that results will be visualized and accepted by others.

2.4 Mr. Roy Evans - Measurement Techniques Panel

A. The techniques selected will largely be dictated by the scenario designed and the site chosen. A small scale tracer study and a full scale power plant study imply different logistics, some of which are outlined below:

1) Height rise - measurements will be simpler in the tracer study because of lower altitude gained by non-buoyant plumes.

2) Mixing height - not scale dependent.

3) Tracer species measurements - the tracer study would use a fixed ground based network to measure tracer species, while the power plant study would involve measuring several different pollutant species.

4) Surface concentrations - simpler in the smaller study.

5) In-plume measurements - more extensive in full scale study. Small scale study is less suited for remote sensing techniques.

6) Source terms - more complex in full scale study.

7) Wind profiles, temperature, and stability - scale is larger in the power plant study so measurements will be more complicated.

B. Questions and Discussion from the Floor:

1) What is the value of aircraft sampling when such techniques as lidar are readily available? The aircraft makes the plume more accessible. Also, it is unlikely that any of the techniques would be accepted without cross-comparison and corroboration with other techniques.

2) It is important to distinguish between concentration fluctuations and plume movements produced by variations in upwind velocity and by turbulence or separated flow over the hill. It would be desirable to correlate concentrations on the hill and upwind velocity fluctuations.

2.5 Dr. Ronald E. Ruff - Data Management and Quality Assurance Panel

A. Considerations related to data collection:

1) A data acquisition plan based on how data are to be recorded is needed. Techniques vary from manual to real-time read-out.

2) The level of acceptable data accuracy must be established in light of instrumental accuracies of about 10-20% and model accuracies of about an order of magnitude.

3) Data should be flagged in some way to indicate its validity.

4) Field review and final checks are necessary in real-time or short times in order to efficiently run the experiment.

B. Considerations related to quality assurance:

1) Instrument Selection

2) Operational Procedures

3) Calibration and Audits

4) Checks on the overall system

5) Data Verification

C. Considerations related to the final product:

1) After the data base is assembled, final validation, corrections, and changes must be made in an interactive way.

3. SUMMARY OF DISCUSSIONS DURING PLENARY SESSIONS

The primary objective of the experiment was established early in the discussions to be that of an end product which would address the regulatory problem by providing a better understanding of impingement concentrations, particularly with respect to the 3-hour standard. The principle controversy arose from considerations of what was the basic approach best suited to achieving that end product (i.e., what size obstacle to study). Other discussions explored the wide variety of topics that could be studied within the framework of a given approach, as well as the specific methods that could be used. The following is a summary of some of the questions raised and comments made during the plenary sessions.

3.1 100 m Hill vs. 400-500 m Hill

While examining the small scale study approach, the Workshop participants became divided over studying a 100 m hill (as suggested in Snyder's strawman, Appendix A) or a somewhat larger hill. In general, those concerned with modeling favored the smaller hill, while those in experimental design and measurements preferred the larger one.

The advantages of the smaller hill were seen to be its simple geometry, its simpler dynamic influences, and alleged smaller costs involved in studying it. In general, the ease of doing the study (for example, being able to move the source around it) would be expected to result in a more complete data base for addressing the impingement problem. Another benefit lay in relating the results from the small hill study with those from fluid modeling, while being one level closer to the real world. It was also argued that the essence of stable conditions is that the flow is independent of height, so the size of the hill is unimportant. Finally, recent experiments in Australia and Great Britain have tied together turbulence and wind measurements on 150 m hills with calculations and laboratory experiments, suggesting that achieving similitude is not out of the question.

The reservations about the 100 m hill centered mainly around the transferability of the results to real world situations. In particular, it was felt that the surface boundary layer and the vertical structure in the lower atmosphere would not be representative of the meteorology at plume level in real cases. Turbulence processes were viewed by some as being critical to the understanding of impaction, and it was feared that the 100 m hill would not allow proper simulation of them. Another point made was that, while the 400 m hill study would involve additional physical complexities such as drainage flow and thermal effects, those complexities are viewed by some participants to be essential in determining plume impaction. In addition, the study of the larger hill would allow the use of more sophisticated techniques and a preliminary estimate was given that the cost would probably not be more than 20-50% higher than for the 100 m hill study.

The outcome of these discussions was that since no concensus could be reached on this issue the decision on what size hill to study was more properly the task of EPA management.

3.2 Small Scale and Large Scale Studies

The consensus of opinion was that both the small and large scale studies ought to be done, with the small scale study coming first chronologically. The discussion on this topic pointed out some of the advantages, disadvantages, and suggestions for each.

The primary advantage of the small scale study (irrespective of the 100 m or 400 m hill controversy) was that its simplicity offered hope for success at a reasonable cost. There was also more flexibility in that the source could be moved, and the study could easily be adapted to examine such questions as those related to GEP considerations or the effects of plume meander. The scale would be small enough that more real time feedback could be available. In addition, it has a close relationship to physical modeling. Also important was the idea that with a smaller obstacle, the opportunities for observing stable flow in the proper direction would be greater.

On the other hand, the large scale study was viewed as close to real world conditions. Many of the instruments could be more effectively used at this scale which would be greater than their limits of resolution. It was suggested that a site be chosen that was not so complex as to preclude physical modeling. Another suggestion was that some of the advantages of the small scale study should be retained by using a non-buoyant tracer and movable source.

In summary, it was expected that a combination of the small and large scale studies would produce the most meaningful results as long as the limitations of each were recognized.

3.3 Measurements

In general, the kinds of measurements desired were independent of the scale of the study, while the specific instruments recommended were heavily influenced by it. At any level, surface concentrations were considered to be paramount. Wind field, stability, and temperature data were also critical, as were turbulence measurements. Flow visualization techniques were emphasized heavily. Data related to source terms and dispersion would also be necessary, and would be more extensive during the large scale study.

As the discussion turned more to the full scale study, the emphasis on more sophisticated techniques increased. Lidar, both ground-based and airborne, was expected to play an important role. In situ aircraft measurements of various parameters also were considered to be an integral part of the measurement arsenal.

While techniques would not always be adaptable to the different scales, it was recognized that transfering as many as possible from the first study to the next would be more cost effective.

3.4 Costs

Relatively little discussion was devoted to costs, however some specific points were made during the plenary sessions on such items as budget division and relative cost of small scale versus large scale studies.

Early in the discussions a suggested budget division was made by the Measurement Techniques and Data Management Panels as follows: Project Management 10%; Field Work and Initial Data Processing 55%; Data Analysis and Quality Assurance 15%; Model Development and Evaluation 20%.

During subsequent sessions, the same panels presented estimated costs for various field program scenarios. The instrumentation alone for a 100 m hill experiment, as originally proposed by Snyder, was estimated to be around \$2.5 million, providing real-time read-out from an array of towers with 8-level instrumentation. These figures were

lowered somewhat as the need for the tower heights and real-time sampling requirements were reduced. It was noted, however, that the small hill experiments would employ costly in-situ measurements which would have to be coarser to offset costs. Also, on the larger scale, the argument was made that more information is returned for the type of sensors in the field.

SECTION 5

PANEL RECOMMENDATIONS

This section contains recommendations to EPA, which were generated by this Workshop through the five panels. They represent the viewpoints, expressed orally and in writing by the panel members, which were organized into comprehensive documents by the Panel Leaders. These statements have been circulated among the panel members for comments before the Panel Leaders submitted them to the Contractor for publication.

It should be noted that very limited time was available for this process. The Panel Leaders would have preferred more time for the demanding review, and organizational and editorial tasks to assure overall continuity and fluency in the statements which follow. However, it was the expressed desire of the Project Officer and Contractor that as much as possible of the written inputs by the panel members should be retained, and that the publishing of the proceedings in a timely manner was more important than editorial perfection of these statements.

The following recommendations prepared by the five panels are presented unabridged as agreed by the Project Officer, Contractor, and Panel Leaders.

1. MODEL DEVELOPMENT AND ANALYSIS PANEL

PANEL LEADER: Bruce Egan

PARTICIPANTS:

Norman Bowne	Jack Cermak
John Clarke	Douglas G. Fox
Philip Gresho	Julian C. R. Hunt
Robert G. Lamb	Jeffery Weil
Robert Wilson	

1. REPORT OF THE MODEL DEVELOPMENT AND ANALYSIS PANEL

1.1 Overview of Deliberations

This panel was concerned with generating the basic approach of the Workshop and the review and selection of the basic scenarios which EPA should follow in their overall program. The panel discussions concentrated on defining what was needed to meet EPA's most pressing needs regarding model improvement for regulatory-oriented applications in complex terrain. The panel's approach was from the perspective of knowing the modeling basis on which EPA regulatory decisions were now commonly made (e.g., on the basis of VALLEY, CRSTER or similar models) and from the conviction that there was considerable room for improving the physical representations inherent in the model algorithms, especially in complex terrain settings.

Implicit in the discussions was the recognition that a descriptive and conclusive measurement program would be required to rectify the discrepancies in the currently used and presented models. For this reason the initial discussions centered on what sort of field programs would be most useful. Later discussions centered on the expected nature of the mathematical modeling effort which would be required both in the short and the long term, the roles that physical models could play in model development, and the uses to be made of the measurement data to be collected.

1.2 Perceived Goals of, and Constraints on, the EPA Program

The panel understood that EPA was primarily concerned with the development of a credible model for regulatory applications involving the near field impact of fossil-fuel fired facilities located in the vicinity of rough terrain. The question of the magnitude of possible plume impingement was of major concern. Other constraints on the program discussed included:

- Overall budget in the range of two to two and a half million dollars per year for about three years.
- A need to produce meaningful and useful end products during the program to help assure the year-to-year funding.
- The program should be designed to have a high probability of success in meeting the goals of EPA.
- The program should be designed to complement other related efforts.
- The program should result in modeling tools with a demonstrated high level of reliability.

1.3 Recommended Approach

The Model Development and Analysis Panel had a consensus that, to meet EPA's goals, objectives, and budgetary constraints, EPA proceed with a two phase research plan which involves:

(1) A detailed study of the interaction of a tracer gas plume with an isolated hill located in otherwise relatively flat terrain. This study should be performed on a physical scale small enough to allow detailed tracer measurements at a large number (of order 100) of locations on the hillside, have the possibility of testing a range of release heights and different release locations, allow the use of a variety of flow visualization techniques, and allow tower-based measurements of wind speed and direction and measures of turbulence at a number of levels above the surrounding plain and above the crest of the hill. We suggest that the data need could be met with a hill of order 100 m high.

(2) A further, larger scale experiment which would build upon the findings of the first experiment, yet still be focused upon obtaining a better understanding of the interaction of an elevated plume with high terrain. This larger scale expriment would allow

the systematic investigation of more phenomena, which in practice further complicates the problem of predicting ambient air quality levels in complex terrain settings. Specifically, this larger scale experiment would require more detailed investigations of the effects of locally-generated, thermally-driven circulations of flow patterns, the magnitude and likelihood of plume impaction, the effects of wind shear on dispersion rates, and the effects that elevated inversions and other phenomena associated with atmospheric stratification have on plume dispersion.

(3) A closely coordinated mathematical model development program having the following elements:

- Initial use of existing and appropriate modeling techniques in the detailed design of both the small scale and large scale studies. This use would help assure that monitoring sites are optimally located for maximum benefit.

- Initial model development oriented toward making maximum use of data to provide reasonable "fix-ups" to Gaussian-based models currently used in regulatory practice. This was expected to take place during the first two years of of the program.

- Subsequent model development activites concentrating on developing and using better descriptions of the flow fields expected in rough terrain for a variety of meteorological and topographic settings. It is anticipated that this effort would result in flow field descriptions which could be used with either Gaussian-plume-based models (by defining trajectories and distortion effects) or with "K theory"-based models.

  This was expected to take place in the later two to four years of the overall program.

- Initial models developed to meet the requirements of routine regulatory use which include; demonstrated improvement over current methods, relatively easy to use and inexpensive to operate, and capable of using a minimum of routinely available input data.

(4) Data analysis efforts keyed to providing a better physical understanding of the phenomena of interest. This will involve qualitative analyses based in part on the results of flow visualization experiments to be performed. The data analysis and model

verification efforts should examine model performance (based on observed vs. predicted comparisons) using different levels of input information. For example, the model performance can be evaluated, using only data from a nearby airport, only data from an on-site meteorological tower, or using the more comprehensive data sets from the detailed measurements to be taken around and on the surface of the experimental hills.

(5) A coordinated and complementary physical modeling program. This program should involve defining the applicability and limitations of the use of physical models (wind tunnel, water towing tank) by comparisons of results with the small scale field program. Based upon the demonstrations of valid uses of the physical modeling techniques, these methods might be applied to expand the data base for testing mathematical models and to better understand the flow behavior for different terrain configurations. The results of these techniques presumably can also be used to help design the larger scale field program.

Figure 2 depicts the expected flow of information among the program elements.

Several other comments about the panel's deliberations and the reporting herein appear important to include at this point:

(1) Some of the initial "scoping" discussions touched upon problems of achieving reliable performance with even significantly improved mathematical models when these were used to predict the highest or second highest concentration values expected during a period of a year, as required by present National Ambient Air Quality Standards (NAAQS) and Prevention of Significant Deterioration (PSD) rules. Panel members agreed that a re-definition of such standards, which would require predicting the highest values occuring a few percent of the time, would make more sense from a modeling point of view. The error bands between modeled and observed values would be expected to be much smaller in this latter case and greater reliability could consequently be put on modeling results.

(2) It was decided that, given the constraints of available time for creating this report and the nature of the material to be covered, it was preferable to not attempt a major editorial effort to make the submission totally non-redundant or consistent in style. It was also felt that such an editorial effort would tend to obscure some of the flavor of individual opinions vs. those better described as panel consensus, and that the report would thereby lose some value to future readers.

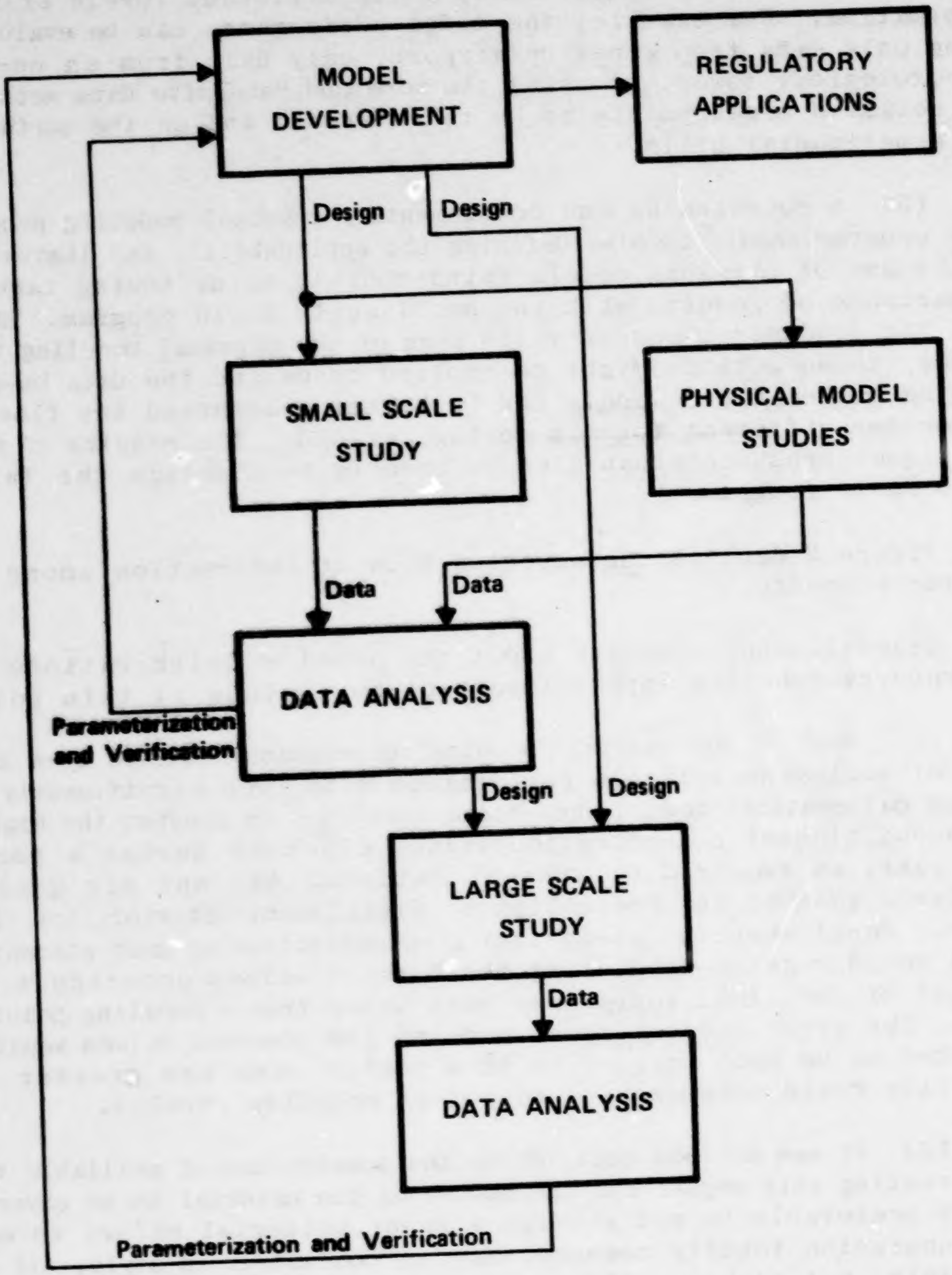
MODEL DEVELOPMENT
REGULATORY APPLICATIONS
Design
Design
SMALL SCALE STUDY
PHYSICAL MODEL STUDIES
Data
Data
DATA ANALYSIS
Parameterization and Verification
Design
Design
LARGE SCALE STUDY
Data
DATA ANALYSIS
Parameterization and Verification

Figure 2. Diagram of flow of information within program.

The remaining sections of this panel's report are basically comprised of contributions by individual panel members who volunteered to summarize specific topics addressed by the Model Development and Analysis Panel. The following topics are addressed:

1. The Small Hill Experiment
2. Model Development Activities
3. Uses of Field Data
4. The Role of Physical Modeling
5. Description of the Full Scale Experimental Program

1.4 The Small Hill Experiment

This panel unanimously agreed that a small scale experiment (100 m) similar to that proposed in Snyder's "Strawman", and focusing on the issue of parameterizing the highest air quality impacts of an upwind source during stable, neutral, and unstable conditions, would be a good choice to meet EPA's immediate goals and constraints. The specific advantages of this experiment, which were cited, include the following:

- The results of this experiment would address the major modeling problems associated with permitting sources located in rough terrain.
- The data offered real hope of success in improving upon presently used modeling methods.
- Significant results could be achieved at reasonable costs.
- The experiment can be inexpensively expanded to also consider issues of Good Engineering Practice (GEP) in the presence of a terrain object.
- The scale and scope of the experiment allowed the possibility of providing real-time or, at least, short-turnaround feedback on the nature of the findings. Along these lines it was strongly felt that having a relatively simple experiment, which was focused on investigating the most important technical issues, would avoid some of the problems which have plagued other large scale experiments attempting to meet very broad objectives.

- The scale of the experiment was sufficiently small to allow extensive use of flow visualization techniques (such as multiple smoke releases on the hill surface) and portable meteorological measurement devices (such as anemometers on short masts) to investigate closely the boundary layer flow on the hillside. The panel felt that such augmentations to the basic measurement program would add greatly to the overall worth of the program by supplying a better fundamental understanding of the flow phenomena of interest.

- The small scale study allowed the possibility of using a relatively mobile source release. Specifically, the fact that the tracer source height could be systematically raised and lowered (perhaps even two sources could be released simultaneously), and moved to varying distances from the hill, gave the experiment both possibilities of examining the relationships (such as source height to hill height ratios), and would result in a higher data capture rate (the source could be moved on a multi-hour basis to be more-or-less upwind of the hill).

The panel identified priorities to be set for the measurements to be made as follows:

(1) Near-ground surface (breathing level or less) measurements of tracer material concentration values in order to provide a direct relationship of emission rates to ambient air concentrations.

(2) Meteorological measurements from several levels on a tower of at least hill height and preferably one and a half hill heights. These measures should include anemometry for the three components of wind speed and turbulence statistics (e.g., sigma theta, sigma E, and standard deviations of vertical and horizontal wind speed fluctuations averaged over 10 minutes or so). Differential temperatures and heat flux measurements should be required. This tower should be located on flat terrain away from the hill at a location where, under prevailing wind conditions, the tower would measure the air flow unaffected by the presence of the hill. A second, similarly instrumented tower (50 m) should be on top of the hill. A few ten to thirty meter towers should be located on the sides of the hill. Tracer measurements should be made on each tower. Meteorological measurements should also include sampling of the vertical temperature structure of the atmosphere (temperature soundings and/or acoustic sounders) and the possible supplemental use of a doppler radar for wind measurements.

(3) Measures (perhaps by remote sensing by lidar of fluorescent particles) of the elevated plume concentrations and geometry upwind of the region of interaction of the hill. Specifically, measures of sigma z and sigma y were very desirable, provided they were taken in sufficient detail or over a sufficiently long averaging time, to produce estimates useful for averaging times as large as one hour.

(4) Flow visualization of flow phenomena - smoke releases, etc. Surface smoke releases should be made simultaneously from 25 to 50 well chosen locations to ensure good definition of the mean flow field. This is essential for reaching an understanding of the fundamental fluid dynamics of the flow over the hill and Reynolds Number effects for comparisons with the physical model results. The smoke can be photographed by aircraft and ground-based cameras.

The 100 m hill experiment ws envisioned to have the following additional characteristics and details:

(a) An "ellipsoidal" hill should be found which allows study of plume behavior approaching both the narrow and broad sides in order to understand the effects of hill aspect ratio on maximum ground-level concentrations.

(b) On the order of one hundred samplers should be positioned on the hill side (not all of which need be run for each experiment). A suggested array is presented in Figure 3.

(c) The panel did not feel that it was necessary to have all concentration measurements in real time or with sampling times of 10 minutes. On the contrary, the concern was expressed that in order to properly understand the effects of wind meanders, etc., a one hour averaging time would be necessary to final interpretation and extrapolation of results. However, it was desirable to have a few continuous and realtime samplers in the experiment. After an experiment is underway, the tracer release should continue from the same location for a duration of at least 3 hours.

(d) The panel also did not feel that it was absolutely essential that the ground-based array be of such close spacing so as to always be able to capture the plume or to always allow direct determinations of the cross-wind or vertical dimensions of the plume. The panel recognized that very narrow plumes might miss the sensors

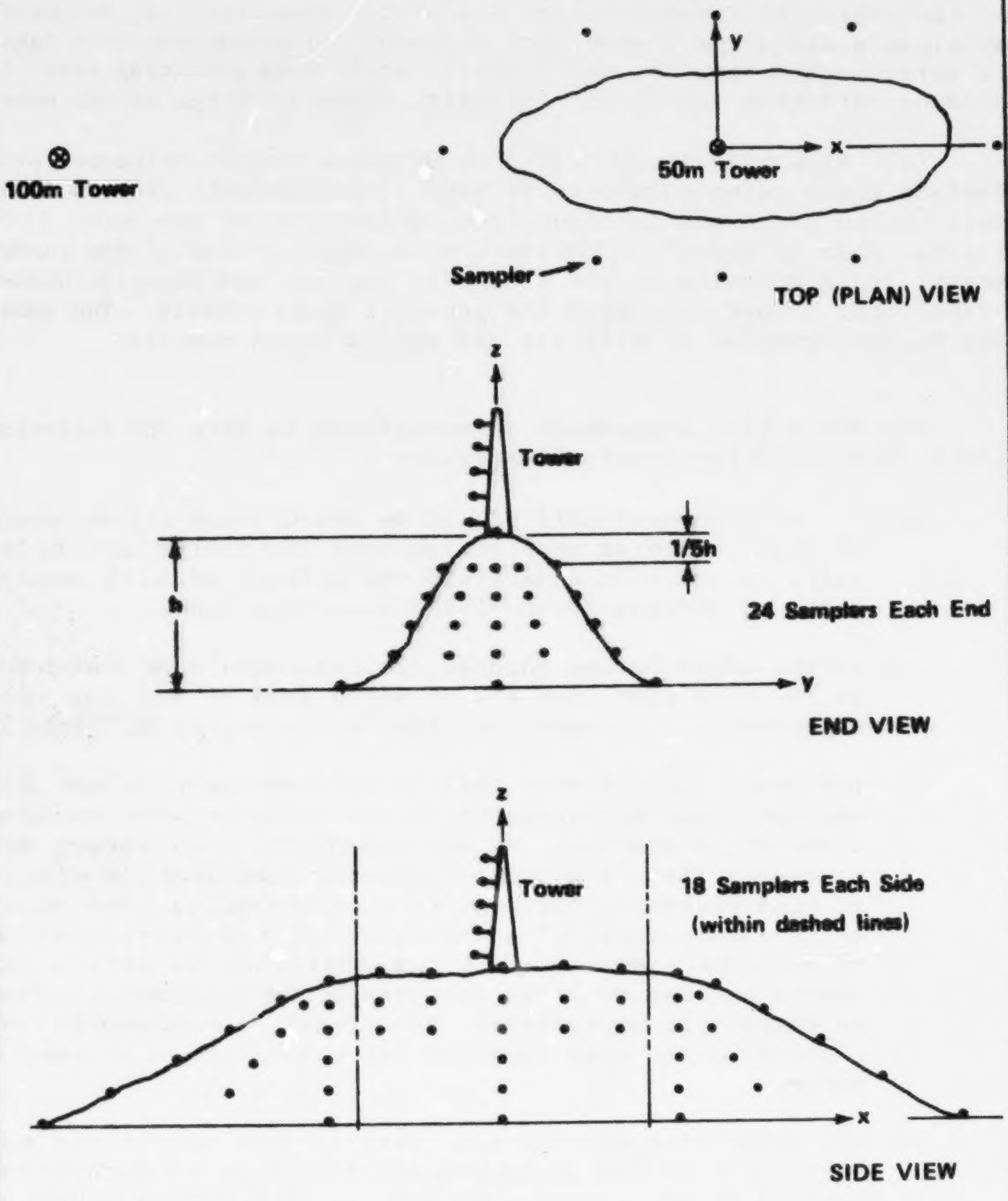
y
x
100m Tower
50m Tower
Sampler
TOP (PLAN) VIEW
z
Tower
1/5h
h
24 Samplers Each End
y
END VIEW
z
Tower
18 Samplers Each Side
(within dashed lines)
x
SIDE VIEW

Figure 3. Suggested array of samplers for 100 m hill experiment.

during some experiments, but if the experiments were performed a sufficient number of times, the largest expected impacts would be observed. The model validation should be focused on values at the high end of the frequency distribution of concentrations - not just the highest values.

(e) Experiments should be run for all meteorological conditions and should not focus solely on behavior during stable conditions.

(f) Several different tracers released at different heights can have the utility of conducting multiple experiments within a single experiment.

(g) Surface temperature fields could be obtained by indirect techniques (IR measurements from aircraft).

(h) The statistics of wind flow onto the hill from a given source location should be examined and related to the statistics of local wind stations.

Specific limitations noted for the small scale experiment are as follows:

(1) The wind and temperature structure that an elevated power plant plume may encounter 300 to 800 m above the surface is not likely to be similar to that through the first 100 m. This, however, is not likely to affect any conclusions relating to the ratio of maximum concentrations in the plume (immediately upwind) to those on the surface.

(2) The small hill is not likely to be as thermally and thus dynamically active as a large hill, i.e., upslope and downslope flow will be unimportant. Also, the surface roughness and processes by which the plume interacts with the immediate surface will not be adequately simulated on the small hill.

(3) Only a limited range of source heights relative to hill height can be examined with a movable tower release. Specifically, it may not be possible to have a release height greater than 70 m. Other methods of releasing the tracer gas from higher elevations should be investigated (e.g., use of a balloon).

(4) The hill is not tall enough to extend up through the radiation inversion depth where variable temperature profiles and

wind shear effects are important, i.e., processes that become important for plumes from large power plants will not be thoroughly considered.

(5) Boundary layer structures, like those found on larger hills of different slopes, will not be considered.

(6) Only flow on a hill having one aspect ratio can be explored in the initial field study. (Note that the physical modeling techniques may prove to be useful in expanding this data base).

Recognizing the limitations of the results of the small scale experiment noted above, the panel believes it will be necessary to also study impingement-related phenomena at a larger scale study once the results of the small scale experiment have been analyzed. However, the small scale experiment is an essential first step.

A debate arose in the general Workshop plenary sessions as to whether the simple single hill experiment should be performed at a site with a 400-500 m hill or at something as small as 100 m. This panel had the point of view that some of the additional flow phenomena to be expected at a 400 m site (local flows become more important, wind shear effects, etc.) would tend to complicate the experiment and the 100 m hill was slightly preferable from this point of view. The major conviction of the panel of the merits of the 100 m size was based, however, on the expectation that the flexibility and data capture possibilities at a 100 m hill site would be severely compromised at a larger scale site. The panel was specifically concerned over the impracticality of constructing a tower of sufficient height, and the logistical problems associated with performing the same experiment on a large scale. The panel also felt that heavier dependence on remote sensing techniques at the larger site would not focus as well on the issue of actual ground-level concentrations.

2. MODEL DEVELOPMENT ACTIVITIES

2.1 Introduction

2.1.1 Objectives. As evident from numerous legal debates, a serious need exists to develop a model capable of accurately predicting concentration, especially maximum ground-level concentration, in the vicinity of proposed sources located in complex topographic environments; that is, locations where the topographic feature height is a significant fraction of the source height (or much greater than stack height).

The proposed model development is strongly guided by existing practice. Since existing practice includes use of VALLEY and CRSTER, the model development should lead to either improved or substitute models. The primary objective of model development is to improve the accuracy of these models in predicting maximum ground-level concentration.

2.1.2 Method. Perhaps the major area of controversy associated with applications of air quality models is plume impaction on nearby elevated terrain surfaces. Recent theoretical developments suggest that under certain stable flow conditions, plumes can impact on terrain. Physical models in stably stratified water channels and wind tunnels of the flows around simple hills have demonstrated that the impaction phenomena predicted does in fact occur, but little information exists regarding the magnitude of this impact.

The model development program will seek to include results from the theoretical developments, the field studies, and the physical modeling experiments in order to provide model simulations of plume impaction. This represents a step toward improving the scientific justification for air quality modeling and a highly important step with regard to application of the models in regulatory proceedings.

For neutral and slightly stable conditions, it is expected that the conventional Gaussian model can be altered to yield acceptable results. For the stably stratified case it may be necessary to introduce a separate formulation.

It is also recognized that all significant situations in the application of air quality models do not involve simple isolated hills. Thus, the model will need to be developed in such a manner that it can be applied to more complex situations. It will therefore need to be tested against other data previously collected in addition to that collected in this program.

Increased complexity in the topographic situation will probably require development of some form of meteorological or flow field simulation in order to properly direct the plume in complex terrain. Consideration should be given to the development and validation of such a technique within the framework of this project and given the constraints of acceptability for regulatory application.

2.2 Constraints on Model Development Program

It was suggested that the modeling program be divided into two phases consistent with immediate and long-term objectives.

2.2.1 Immediate (1-2 Years). This phase is closely coupled to the small-hill impaction study and should observe the following ground rules:

a. Should result in useable and valid improvements to the VALLEY and CRSTER models.

b. Should be easy and inexpensive (computer resources) to use.

c. Should require a minimum of input data.

d. Should be successful in simulating surface concentrations from the small-hill study over the range of plume impingement phenomena under very stable to neutral stability conditions. Stability in this context is being characterized by the Froude number (Fr) of the upstream approach flow given by Fr = U/Nh, where U is the velocity at hill height, h, and N is the Brunt-Vaisala frequency.

The implication of these ground rules is that: (a) proposals for changes in existing approved models be given priority; (b) a variety of existing approaches should be studied; (c) little totally new work can really be developed (i.e., the first phase modeling will be based on the Gaussian-type models).

2.2.2 Long-Term (2-4 Years). This phase will build on the first phase, generalize the model where possible, and be developed simultaneously with the design and (perhaps) implementation of the full scale study. The following ground rules apply.

1. Improved methods of estimating the transport wind field for application to new "sites" are required. Locally driven surface flows (upslope, drainage, etc.) should be considered for inclusion, as well as a first estimate of other effects caused by complex terrain such as vertical variation (shear) of the wind.

2. Should be reasonably economic in terms of computer resources (storage/execution time).

3. Should also "succeed" in describing experimental results from the earlier small-hill study.

4. Should be capable of treating different situations equitably in regulatory applications.

The implications of the above led to the following suggestions for longer term model development activities:

(1) A review of the state of knowledge in diagnostic wind modeling on scales up to 200 km

(2) Development of a complex topography flow field data set stable and neutral (perhaps also unstable) conditions for for testing diagnostic wind models

(3) Early (within 2 years) selection of, at least, a generic model to diagnose wind fields

(4) Utilization of the generic model approach to provide guidance in design of the second phase field experiment

(5) Study of Gaussian and other parameterizations of plume turbulence for coupling diffusion with the flow model

(6) Final verification and testing against field programs of combined approach and initiation of the process to include the new model in OAQPS guidelines.

2.3 Immediate Model Development

The following steps are suggested:

(1) Consideration of the state of knowledge (capability) in modeling source emissions in complex topography including recent theoretical developments of stratified flow theory and results of wind tunnel and water channel experiments simulating plume behavior in stratified and neutral flow. This effort should focus on the potential use of:

  (a) 2-D potential flow theory as an approximation of the mean streamlines in the horizontal plane for highly stable conditions (Froude number much less than one);

  (b) linearized theory (small amplitude, inviscid approximation for moderately stable conditions (Froude number about one); and

  (c) potential flow theory for the windward side of terrain features during near neutral conditions.

The ability of such approximations to adequately simulate interactions between closely spaced topographic elements where the flow is dominated by the shedding of vorticity should be carefully studied. This effort should also review recent findings regarding the motion of stagnation points due to downstream vortex shedding, diffusion rates when temperature gradients vary considerably over the terrain object, the effects of slope winds on plume centerline trajectories, and the most appropriate ways of parameterizing plume dispersion in separated flow regimes.

(2) Critical review of existing "Recommended" (albeit defacto recommendation) modeling algorithms, i.e., CRSTER and VALLEY as well as other Gaussian-based models. Compare model algorithms and assumptions with theory and experimental results as identified in (1) above. Develop a "matrix" of proposed improvements which considers changes in the parameterization in the Gaussian based models of: horizontal and vertical diffusion, plume trajectory alterations, stability classifications, and space and time averaging effects.

(3) Proposed alterations of Gaussian-based models to include results of 1-2. This would include consideration of each component "parameterization" in models such as VALLEY and CRSTER and the "matrix" of proposed improvements. This effort could, among other alternatives, attempt to introduce terrain correction factors into the Gaussian methodology and use combinations of diagnostic flow models with various diffusion parameterizations to simulate transport and diffusion in complex topography.

(4) Develop/adopt standards of performance for a complex topography model consistent with those included in the EPA modeling guideline and having a sound technical basis.

(5) Testing of the matrix of improvements against the field data collected by this study.

(6) Final recommendation of specific improvements.

2.4 Long-Term Models

2.4.1 Diagnostic Wind Field Modeling. Since even the best of the first generation (immediate) models may stumble in new and seriously complex terrain situations, owing, in large part, to the lack of an adequate (realistic) wind field, the next generation of models should be directed toward ameliorating this deficiency. Another concern is the increased opportunity for misapplication of such model vis-a-vis flat terrain Gaussian models. Towards this end, models which generate (diagnostically) some sort of a reasonable 3-D wind field should be developed and coupled to either (a) a modified Gaussian model, or (b) a numerical solution methodology for the advection-diffusion equation. This model could be based on input data of varying degrees of detail, ranging from climatological averages to a selection of site specific measured winds. In all cases, the input data would be used to generate an improved estimate of the 3-D wind field at a set of grid points, the bottom surface of which represents the topography. Small-scale physical models are expected to be useful in the evaluation of such models.

The spectrum of such modeling approaches is fairly broad, ranging from those which simply generate wind fields conserving mass (and do not penetrate topography) to those in which additional physics is simulated. Hopefully, the best of these could include effects of stratified flow, perhaps via a Froude number modification.

2.4.2 Toward the "Ultimate" Model. Again it must be borne in mind, when examining the limitations of the second generation models that even the best of these (which could be one combining the best features of these currently available), even after being "calibrated" via the full-cale field data, may not always perform well in new and different topographic settings. The reason for this is, as before, that such models contain insufficient physics to always reliably generate wind fields which are strongly affected by details such as terrain shape and small-scale driving forces (e.g., drainage wind and upslope winds), or even large-scale effects such as mountain lee waves and the strong downslope winds often assocated with these.

Although a fully comprehensive model would be a desirable end product, and would be much more generally applicable, it is recognized that such a model development program not only requires much more time and effort than is allotted under the ground rules, but requires a greater understanding of flow behavior under a variety of complex conditions than is likely to be available. For these reasons, it is prudent at this time to restrain model development as discussed earlier.

Nevertheless, it is appropriate to briefly discuss such comprehensive models in the event that future programs recognizing the need are planned, or that simpler models are found to be inadequately extrapolative. The comprehensive model would be one which solves a finite difference approximation to the equations of mass momentum, and energy conservation on a set of grid points which includes an accurate topographic description. The transport modeling could be performed, using finite difference or finite element methods, and turbulence could be modeled either via first-order (K-theory, with locally varying diffusion coefficients) or second-order method, either of which must recognize and address the current shortcomings of turbulence parameterization. Currently such methods give no idea of the statistics of concentration fluctuations (i.e., the effects of averaging times) and cannot be used for unsteady flows. Random walk techniques may be as, or more, appropriate. Once such a model is developed, it could be calibrated in the following ways: (1) Numerous simulations of wind tunnel results covering a wide range of topographic and thermal variations (some of which will have, hopefully, been verified against field data) and (2) Several field study data sets, depending largely on their availability (the data set obtained from the full scale test of this project is a prime candidate) and completeness. Such an approach, while significantly more complex, costly, and time consuming (both in development and in computer time), would appear to have a high probability of ultimate success and could lead to a model which is truly general and confidently applicable to new and different potential sites.

3. USES OF FIELD DATA

3.1 Summary

In this section of the report we consider the uses of the data from the small and large scale field experiments. This section is divided into two broad subdivisions.

1. Comparing the data with models, qualitative mathematical and physical.
2. Using the data for improving the models (especially those currently used by EPA (e.g., VALLEY, CRSTER)).

3.2 Comparing the Data with Models

3.2.1 Qualitative Models. Many air pollution regulatory decisions are ultimately (explicitly or implicitly) based on qualitative models of the flow patterns and plume trajectories. Therefore, the first use of the data, especially flow visualization data, must be to help better define these qualitative models and to reduce the areas of controversy surrounding them. Specific items for analysis are:

(a) Identify the range of temperature gradients and wind speeds that the air flow passes around or over the hill.

(b) Compare the nature of the separated flow regions as a function of Froude number with laboratory experiments.

(c) Identify conditions when plumes are prevented from impinging into hills or valleys by downslope winds and when they fumigate onto hills.

3.2.2 Mathematical and Physical Modeling. The general approach governing the comparison between the field data and mathematical or physical models should be to: 1) use the data governing the approach flow [e.g., velocity field, turbulence measures, temperature profile, height and quantity of plume release, nature of the hill, etc.] to predict various aspects of the velocity and concentration distributions over the hill, and 2) to then compare these with the observations.

A list of some of the useful predictions and comparisons should include:

(1) Comparisons of surface flow patterns over the hill (based on smoke visualization) with model predictions as a function of Froude number and surface heating/cooling rates.

(2) Mean plume trajectories. These can be calculated using potential flow theory for simple hill shapes a priori from the hill geometry and given Fr and compared with the observations.

(3) The frequency of impinging plumes and the local plume meander in stable conditions. These can be related mathematically to local wind statistics and perhaps the wind statistics from a nearby meteorological station.

(4) If possible the velocity and turbulence structure over the hill top should be compared with other neutral field experiments and mathematical/physical model studies.

(5) In the larger field experiment, significant measures of up and down slope winds are expected including the depth thickness, velocity, and turbulence of these winds (e.g., in the Navajo Vermillian cliffs experiments large up and down slope winds were observed with velocities of the order of 5-10 m/s and with layer thicknesses of 20-30 m). These measurements should be compared with theoretical values.

(6) The observed spread statistics, σ_z, σ_y, and maximum concentration upwind of the hill, on the hill, and over the hill, should be compared with complex terrain calculations based on:

(a) Pasquill-Gifford spread statistics.

(b) Local upwind measurements of velocity fluctuation statistics, and the upwind temperature gradient.

(c) Measurements over the hill of velocity fluctuation statistics, $\sigma(z)$, temperature and wind profiles and the plume centerline locations.

(7) Compare the ratio of the surface concentration on the hill at one point to the plume centerline concentration immediately upwind of this point. Since the location of maximum surface concentration varies quite rapidly as the wind direction changes, it is important that these be compared as a function of the averaging times of the plume measurements and of the ground-level concentrations. These data will help considerably in interpreting previous field studies where the averaging times were frequently different.

3.3 Using The Data for Improving Models

3.3.1 VALLEY Model

(1) Impact Ratio. One major use of the experimental data should be to define the ratio of the maximum ground-level concentration on elevated terrain to the plume centerline concentration immediately upwind of the terrain. These values can be obtained from the small-scale study as a function of flow field conditions.

The EPA VALLEY model assumes total ground reflection of the plume, resulting in a ratio of 2.0, which is thought by some to be conservative.

The measured values of the ratio should be compared to values calculated by mathematical models and measured by physical models.

The satisfactory agreement of the model estimates with measured values would allow the applicability of models to be extended to flow, terrain, and heating/cooling conditions not measured in the experiment(s).

(2) The Assumed Plume Width σ_y. Currently the 24-hour average concentration is based on assuming that the plume is spread out over a 22 1/2° sector. This assumption must be compared with observations and possibly some improved way of estimating this sector may emerge.

(3) Statistics of Plume Impingement. This leads to the next major use for experimental data, which is to determine the frequency of occurrence and persistence of terrain impact flow conditions in complex terrain. This should be accomplished through long-term (at least one year) continuous meteorological measurements to arrive at hourly average flow conditions. Such data should provide the necessary input to the mathematical model for determining second highest concentrations for a given source during a year for various averaging times, e.g., 3-hour and 24-hour. These estimates will be site-specific. However, recommendations might then be derived which would be generally applicable for specification of the minimum (number and type) of meteorological measurements needed at complex terrain sites to determine the frequency of occurrence and persistence of terrain impact flow conditions. When a significant source of pollutants is proposed for location in complex terrain, these recommendations can be used to specify the necessary site-specific data to show compliance with regulatory standards.

(4) Plume Downwind of a Hill. Currently the VALLEY model assumes that a plume travels on downwind of a hill with no change of dispersion rates. Physical models suggest that the plume widens out to the hill's width, b, so that its concentration is decreased by (b/σ_y) where σ_y is the plume width prior to impingement. Hopefully this aspect of VALLEY could be improved. (σ_z is also expected to increase downwind).

(5) Application of VALLEY Model. Currently this model is applied when dT/dz is greater than a critical value. Physical and mathematical modeling suggests very strongly that the criteria for the application of this kind of model should be based on the value of a dimensionless number such as the Froude number.

(6) Criterion for Flow Pattern. As indicated earlier, Fr should be criterion for the flow pattern and for the plume impingement. Hopefully, this study should also indicate when strong up or

downslope flows may alter this criterion and change the value of the impact ratio.

3.3.2 Moderate Stability and Neutral Flow Models

(1) Terrain Following Models. In some models when the temperature gradient is less than a critical value, a neutral flow model of the flow is used. The simplest of such models assumes that the plumes follow a trajectory which remains at the same source - displacement above the hill. Clearly the experimental results should be compared with this model, and the differences noted. We anticipate that this model will drastically underestimate maximum surface concentration - especially for three-dimensional situations.

(2) Interpolative Models. In such models some allowance is made for the trajectory approaching the hill surface (e.g., half-height models). This approach is an improvement but is likely to be insufficient in many applications.

(3) New Models. New models being developed under EPA contract are oriented toward regulatory use and may form the basis of improved techniques. If so, they should be carefully compared with the data in both a regulatory manner as well as in a more scientific manner.

4. THE ROLE OF PHYSICAL MODELING

In the last two decades physical modeling of the atmospheric boundary layer has advanced to a state that permits accurate predictions of atmospheric transport and dispersion for many sites and meteorological conditions. Two types of facilities have been developed that enable thermal stratification of the lower atmosphere to be simulated. These are the meteorological boundary layer wind and the towing tank (water channel). Model studies of flow and dispersion around an isolated hill are proposed to: a) complement data obtained from the field study, b) check the degree of similarity between small-scale model and full-scale data, and c) determine the relative merits of the two physical modeling methods.

4.1 Background

The first attempt to study stably stratified flow over a topographic obstacle in the laboratory was made by Abe (1929). Flow over dry ice in a small wind tunnel produced a crescent lee wave downwind of a 1:50,000 scale model of Mt. Fuji that was in qualitative agreement with full-scale observations.

In 1934 Prandtl and Reichardt (1934) designed and constructed the first meteorological wind tunnel with a capability for development of a thermally stratified boundary layer. This facility was destroyed during World War II before being put to its intended use. Following these early developments Cermak (1958) designed and constructed a meteorological boundary layer wind tunnel at Colorado State University. This facility and details of the early developments are described in a paper by Cermak (1975). The 30 m long test-section of 2 x 2 m cross-section is equipped with a floor that can be cooled (or heated). Air heated (or cooled) in the return duct develops stably (unstably) stratified boundary layers 1 m thick with temperature differentials up to 200°F. This wind tunnel is well suited for physical modeling of either stable or unstable flow over an isolated hill.

The history of towing tanks to study atmospheric motion is somewhat obscure. References to some early developments, and a description of the towing tank proposed for physical modeling of flow over an isolated hill, are given by Hunt, Snyder and Lawson (1978). The channel is 1 - 2 m deep, 2.4 m wide and 25 m long. The model is towed on a ground board through water that is stably stratified by a linear salt-concentration gradient.

Physical modeling of flow and dispersion around the isolated hill in both facilities is recommended, since each type of facility offers distinct modeling advantages and disadvantages. Therefore, comparison with full-scale results will help advance the science of physical modeling while providing data to complement the field study.

4.2 Modeling Criteria

Similarity criteria for physical modeling of the atmospheric boundary layer are given by Cermak (1971) and Snyder (1972). A discussion of similarity for stably stratified flow around an isolated hill is presented in Hunt, Snyder and Lawson (ibid).

Two types of similarity should be considered - similarity of the atmospheric boundary layer approaching the hill, and similarity of local flow around the hill. As discussed by Cermak (1971), the boundary-layer characteristics (excepting for turning of mean wind direction with height) will be similar if the following conditions are met:

1. Equality of bulk Richardson No. $(\Delta\overline{T}/\overline{T})gL/U_o^2$ (L = vertical distances used to determine temperature difference, $\Delta\overline{T}$).

2. Equality of Relative Roughness K_s/L_o for Upwind Approach; (L_o = length of upwind boundary; K_s = equivalent height of roughness elements).

3. Reynolds No. $UL_o/(\nu)$ in excess of value required to make drag coefficient independent of K_s/L_b. On smooth hills the location and extent of separation appears to be a sensitive function of Reynolds number as well as K_s/L_b.

4. Equality of relative boundary layer thickness δ/h, (h = height of hill, δ = boundary layer thickness).

Local flow around the hill is expected to be similar if, in addition to satisfying the foregoing conditions, the following conditions are met:

1. Equality of Relative Roughness, K_s/h.

2. Hill-Reynolds No. $Uh/(\nu)$ is in excess of value required to give similar location of separation for given value of K_s/h.

3. Equality of product of Hill-Richardson and Reynolds Nos. (This is a tentative relationship which needs experimental confirmation).

$$g \frac{\Delta\overline{T}_s}{\overline{T}} \frac{h}{U^2_h} \left(\frac{U_h h}{\nu}\right) = g \frac{\Delta\overline{T}_s}{\overline{T}} \frac{h^2}{U_h \nu}$$

T_s = difference in temperature between hill surface and air.

4. Model hill is geometrically similar to prototype hill.

5. Surface-temperature distributions are similar for model and prototype hill. Frequently the Richardson No. for approach-flow similarity is replaced by the square root of its reciprocal - the Froude No. $U/[(\Delta P/p)gh]^{1/2}$ (Hunt et al, 1978).

4.3 Similarity in the Meteorological Wind Tunnel

In the meteorological boundary-layer wind tunnel, the approach-flow similarity parameters can be set to cover the following ranges:

1. Bulk Richardson No. (for entire boundary-layer depth) -40 (unstable) to +20 (stable).

2. Relative roughness of upwind approach - as required for site.

3. Reynolds No. - usually well above minimum required since L_b = 30 m.

4. Relative boundary layer thickness - approximately equal to prototype value. A length scale of approximately 1:300 is suggested for the 100 m hill; therefore, the value of δ/h will be about 3 for the model.

Local flow similarity parameters can be varied as follows:

1. Relative roughness of hill - equal to prototype.

2. Reynolds No. - approximately 7000 minimum for 100 m hill or 1:300 scale ($U \cong 1$ ft/s; $h \approx 1$ ft; $\nu \approx 1.5 \times 10^{-4}$ ft^2/s).

3. Richardson and Reynolds Nos. on the hill cannot be made equal to prototype because of h^2 dependence. Therefore, gravity flows induced by heating and/or cooling the hill may not be similar to full scale.

4. Geometrical similarity - as required.

In terms of the hill Froude number, the approach flow can be adjusted in the range 0.4 to infinity for the stable case and the same magnitude of parameter change for unstable flow. Thus, a wide range of meteorological conditions can be simulated, including an elevated inversion. The latter condition is created by cooling the upstream wind tunnel floor and warming a length of floor upstream of the model.

4.4 Similarity in the Towing Tank

The approach, flow similarity parameters, can be set to cover the following ranges:

1. Richardson No. - in terms of the hill Froude No., the range of values is 0.1 to infinity (neutral flow).

2. Relative Roughness of Upwind Approach - because of short ground board, equality of this parameter is not achieved.

3. Reynolds No. - L_b is ordinarily too small to achieve sufficiently large values.

4. Relative boundary thickness - not equal ($\delta/h<1$).

Local - flow similarity parameters can be varied as follows:

1. Relative roughness of hill - equal to prototype.

2. Reynolds No. - approximately 25,000 ($U \cong 0.5$ ft/s, $h \cong 1$ ft, ($\nu \cong 2 \times 10^{-5}$ ft^2/s).

3. Hill-Richardson No. x Hill-Reynolds No. - same difficulty as for wind tunnel.

4. Geometrical similarity - as required.

4.5 Relative Merits of Wind Tunnel and Towing Tank

In summary, the foregoing considerations of similarity reveal the following relative capabilities of the meteorological wind tunnel and the towing tank for physical modeling of flow over an isolated hill:

	Meteorological Wind Tunnel	Towing Tank
1. Approach - flow velocity boundary layer.	Excellent	Poor
2. Approach - flow density stratification (Froude No.)		
Stable	Good	Excellent
Unstable	Good	Not Feasible
Elevated Inversion	Good	Good
3. Hill Reynolds No.	Good	Good
4. Hill gravity flow (Hill-Richardson No. x Hill-Reynolds No. Comparison of model and full-scale data will help to determine how well flow generated by surface heating or cooling can be simulated).	?	?

For Froude No's. less than one, full simulation of the approach boundary layer may be relatively unimportant for achievement of representative flow around the hill. This is true because flow passes largely around the hill with little change of elevation and the approach flow is quasi-laminar. However, for Froude No's. greater than one, the upstream flow will almost certainly be turbulent and an upwind plume may be transported over the hill surface in the boundary layer flow. Accordingly, the towing tank has some advantage for study of plume impingement at extremely low Froude No's. (including a range of 0.1 to 0.4 that the wind tunnel cannot achieve). On the other hand, the wind tunnel has an advantage that plume impingement can be studied for Froude No's. from 0.4 to 1 and from 1 to infinity where simulation of the upwind boundary layer is essential. Thus, through physical modeling in both types of facility almost all conditions encountered in the field (excepting for some meandering and low-level jets) can be simulated. Furthermore, for Froude No's. in the range of 0.4 to 1 both types of facilities should provide good simulation and thus provide a good basis for comparison of results.

The minimum hill Reynolds No. $Uh/z\nu$ should exceed 10^3 for both facilities. Therefore, unsteadiness of the impinging flow due to vortex shedding from the hill should be representative of full-scale behavior. At these Reynolds No's. it is possible for the boundary layer on the hill (for a sufficiently rough surface) to be quasi-turbulent and provide an accurate simulation of dispersion near the surface.

Simulation of up-slope and down-slope winds on the hill created by heating and cooling of the surface is still in the research state. Full-scale values of the product of Hill-Richardson No. and Hill-Reynolds No. cannot be attained by the small-scale models because of dependence upon the length scale squared. Therefore, a satisfactory modeling of this phase of flow can be achieved only if dependence upon this product becomes weak at some attainable value of the product.

There are several potential benefits to be derived from a comparison of physical-model simulations of flow and dispersion about the isolated hill to the field observations. Principally, the comparisons would demonstrate the applicability and/or show the limitations of physical models to this situation. This demonstration is especially important for strongly stable flows (F 0.1) past hills, where plume impingement can occur. Assuming that satisfactory correlation is achieved between the physical model simulations and field observations, this study would support further use of physical models in basic or generic investigations of flow about obstacles (such as those of Hunt, Snyder and Lawson (ibid), Kitabayshi, et al, (1971), and Lin and Binder (1967). It would also lend credibility to the use of physical models in site specific studies in complex terrain where information is required on the maximum surface concentrations. Furthermore, the measurements on flow and surface concentrations from physical models could be used with confidence in testing mathematical models.

Presently, the simulation of thermally induced upslope/downslope winds in laboratory models is in the developing stage. A combined simulation of these winds superimposed on a mean flow toward a surface obstacle is not foreseen too likely in the early part of the research program. However, in a few years such a combined simulation may be possible. Simulation of thermally induced winds would be more critical in laboratory modeling of flow about the large scale (several hundred meters) terrain feature.

5. DESCRIPTION OF FULL SCALE EXPERIMENTAL PROGRAM

5.1 Objectives

The objectives of the full scale program are developed on the assumption that a small scale experimental program is conducted at an isolated hill to define the relationship between impingement concentrations and those of the unimpeded plume. Objectives are listed in order of priority.

5.1.1 Definition of Flow Fields. A major problem in complex terrain is the definition of the wind field and the resultant trajectory of material introduced into the air. Since the transport of the plume must be known, at a minimum, the wind flow at plume height must be defined in detail. Coupling the transport flow fields at the complex site to the geostrophic flow field may permit a method of transferability to be developed. At the other extreme, the local flow field may be coupled to a physical model in a tank or tunnel. There are simple models of terrain modified wind fields in existence that provide a mean wind in the surface layer. Evaluation of these models can be made from a suitable observation program. If they provide satisfactory estimates of the transport flow field, a major portion of the complex terrain problem will be solved.

5.1.2 Impingement. The major concern of the EPA is the impingement problem, that is what is the maximum concentration at ground level when the plume impacts elevated terrain? The second objective of the complex site study is to determine if findings regarding impingement can be transferred from the small scale study to the full scale site. The study should develop ratios of maximum ground-level concentration to free plume concentrations as a function of differences in the physical and meteorological characteristics of the sites.

5.1.3 Understanding Physical Processes. A comparison of impingement effects could be made on the basis of statistics, but that would preclude transferability of the results to other sites. An understanding of the physical processes involved in the transport, dispersion, and impaction of the plume is a primary scientific objective. The individual processes of concern include plume impingement, occurrence of upslope or downslope and valley winds, downwash or wake effects, depth of slope winds as a function of surface temperature field, local turbulence and effect on concentrations and the influence of topography on the transporting flow field.

5.2 Measurements Required to Meet Objectives

The measurements required to meet the objectives are discussed in the following sections in the same order as the objectives were set forth.

5.2.1 Flow Fields. Measurement of the flow field may be measured by a combination of conventional anemometry on towers near the source and on prominent terrain features, doppler acoustic sounders and perhaps tetroons.

Surface wind measurements will provide information on slope winds. Since the primary objective of knowing the flow field is to determine plume trajectories, it would seem that direct measurement of actual plume trajectories would be most useful. This could be accomplished by aircraft mounted lidar tracking.

The time scale of observations should be sufficient to evaluate turbulence, but short enough to approximate straight line segments. Average values of direction and speed for periods of 10 minutes, to not more than one hour, are considered appropriate. Spatial scales are unknown at this time and are dependent on how much the topography actually influences wind flow at plume height. Comparison of plume or tetroon trajectories, with mixed measurements provided by towers and doppler acoustic sounders recommended here, should provide answers to this problem. The outcome of an intensive plume tracking experiment in this program should be directed to supplying requirements for a minimum density of measurement devices. Rawinsonde observations should be made to tie local observations to the routine synoptic scale observations.

5.2.2 Impingement. Direct measurement of impingement concentrations must be made on prominent terrain obstacles subject to impingement. The time scale of concentration measurement must be appropriate to the air quality standard. Consecutive hourly values that can be averaged for periods up to 24-hours are required. In addition, a measure of plume concentration in the free air prior to, but close to, the impingement point must be measured. The time average of this free air measurement must be the same as the basic time of averaging of the ground-level concentration. The source term, that is the emission rate of the quantity whose concentration is being measured, must be known.

Spatial variability of concentration patternss will be high. It is not practical to have enough sensors on the terrain obstable to define the maximum. A rule-of-thumb generated years ago states that there should be 10 samplers in six standard deviations of the Gaussian plume to define the maximum concentration with good reliability. Even using tracer samplers such density is unlikely. However, continuous sampling to achieve a large number of samples with time rather than space can be substituted in an attempt to capture the maximum concentration. Therefore, continuous sampling is recommended. Physical modeling may be used for development of flow fields, fill-in concentration and wind fields, and provide a basis for model-prototype comparison to evaluate validity of model results.

5.2.3 Physical Processes. In the section on objectives, it was noted that the ability to transfer results to other complex sites is desired. In order to understand the physical processes listed in Section 5.1.3, the necessary measurements must be made in adequate detail. These are listed and discussed.

Impingement frequency - a combination of plume visualization and surface measurements is required. The areas where impingement is expected on the basis of climatology and physical modeling should have measurement capability. Plume tracking by lidar or photography of a visible plume will also provide such data. There must be enough observations to describe the frequency of occurrence of impingement with respect to specified flow patterns.

Slope winds - it is expected that upslope and downslope winds will be major mechanisms affecting plume concentration at the ground. The occurrence, strength, and depth of the slope winds should be measured by local anemometry or with visual means, such as smoke tracers and photography, to establish the relationship between observed concentration and flow. Measures of ground temperature and surface heat flux are also required. Hourly averages should be sufficient.

Downwash or wake effects - if the plume is in the lee of a ridge or hill affecting the vertical position of the plume, the magnitude of the displacement should be documented by indirect measurements with lidar or DIAL systems. The measurements should be sufficient to establish any wave pattern with distance, as well as fluctuations in heights, at a fixed point. Hourly mean values with estimates of the fluctuations, if the fluctuations affect the final stabilization height or ground-level concentration, are required. Wakes behind obstacles, such as an isolated hill or ridge lines, may seriously deform the plume. If such events occur, they should be measured by indirect means such as lidar or COSPEC. Concentration will probably be too low for successful use of a DIAL system. The expended width and/or depth of the plume should be measured and analyzed as a function of obstacle parameters and plume size before encountering the obstacle.

Slope wind depth - if slope winds are found to affect ground-level concentration, then it will be necessary to analyze them in more detail. It has been suggested that slope winds may be categorized as to depth and strength as a function of surface temperature. Radiometric measurement of surface temperature by aircraft mapping or regular thermometry may be used. A need for hourly values over a wide area would suggest standard methods rather than aircraft sensing.

Local turbulence - the local turbulence will be responsible for diffusing a laminar plume flow onto the hillside in stably stratified conditions. But plume meander, which strongly affects the concentration at a point, is not caused by local turbulence, but by unsteadiness in airflow around the topography (e.g., vortex shedding). If local turbulence is a function of surface roughness and heating (and it better be), then direct measurement of turbulence intensity should be related to local concentration. If the relationship is measured at several points to establish patterns and if patterns are found to exist in a quantifiable form, then a method of transferring findings to another site exists. The turbulence measures should be averaged over the same time period as the basic concentration measurement, i.e., one hour or less.

Influence of topography - in Section 2.1 it was noted that the topography influence on plume trajectory was important and that trajectories would be studied. The purpose of this section is to provide measurements, either direct plume measurements or indirectly by wind measurement, of the influence of specific terrain obstacles on the wind pattern at plume altitude. The purpose is to establish standing patterns as a function of geostrophic wind direction and terrain aspect ratio. Hourly averages should provide sufficient time resolution.

5.3 Description of Field Program

The previous sections outlined the objectives and the measurements necessary to meet those objectives. The measurements were stated on an individual basis. In this section we provide an overview of our estimate of the field program necessary to obtain the measurements in an integrated manner.

Figure 4 is a sketch of the field program except for pollutant or tracer ground-level concentration measurement sites. Routine measurement of some variables are called for all the time. Intensive periods of measurements are interspersed for more detail.

5.3.1 Routine Measurements. A meteorological tower of at least 100 meters should be erected, if it doesn't already exist at the site, to measure temperature, temperature difference, wind speed and direction, and turbulence near the source on a continuous basis. Additional shorter towers should be located on the top of the hill to measure wind speed and direction, temperature, and turbulence. Turbulence measurements should be three-dimensional. Other anemometers and temperature devices should be placed in the valley and on the valley sides to measure slope winds routinely. Two u,v doppler acoustic sounders should be employed in the valley to profile the wind above the tower. Rawinsonde observations should be made 2 to 4 times per day. These routine observations will establish the general climatology of the temperature and flow fields of the area.

Routine measurements of ambient concentrations of stack gases should be made to establish concentration patterns. Fifteen to twenty fixed monitoring stations should be located on prominent terrain features and in the valley to establish the annual distribution of pollution patterns and frequency distributions of concentrations at a point. Hourly averages should be acquired. Pollutants to be measured, in order of priority, are SO_2, NO-NO_x, and O_3. In addition, routine high volume air sampling for total suspended and respirable particulates should be carried out on a 24-hour basis.

5.3.2 Intensive Periods. Intensive measurement periods of 4 to 6 weeks duration should be carried on as usual, but additional, more detailed measurements would be added.

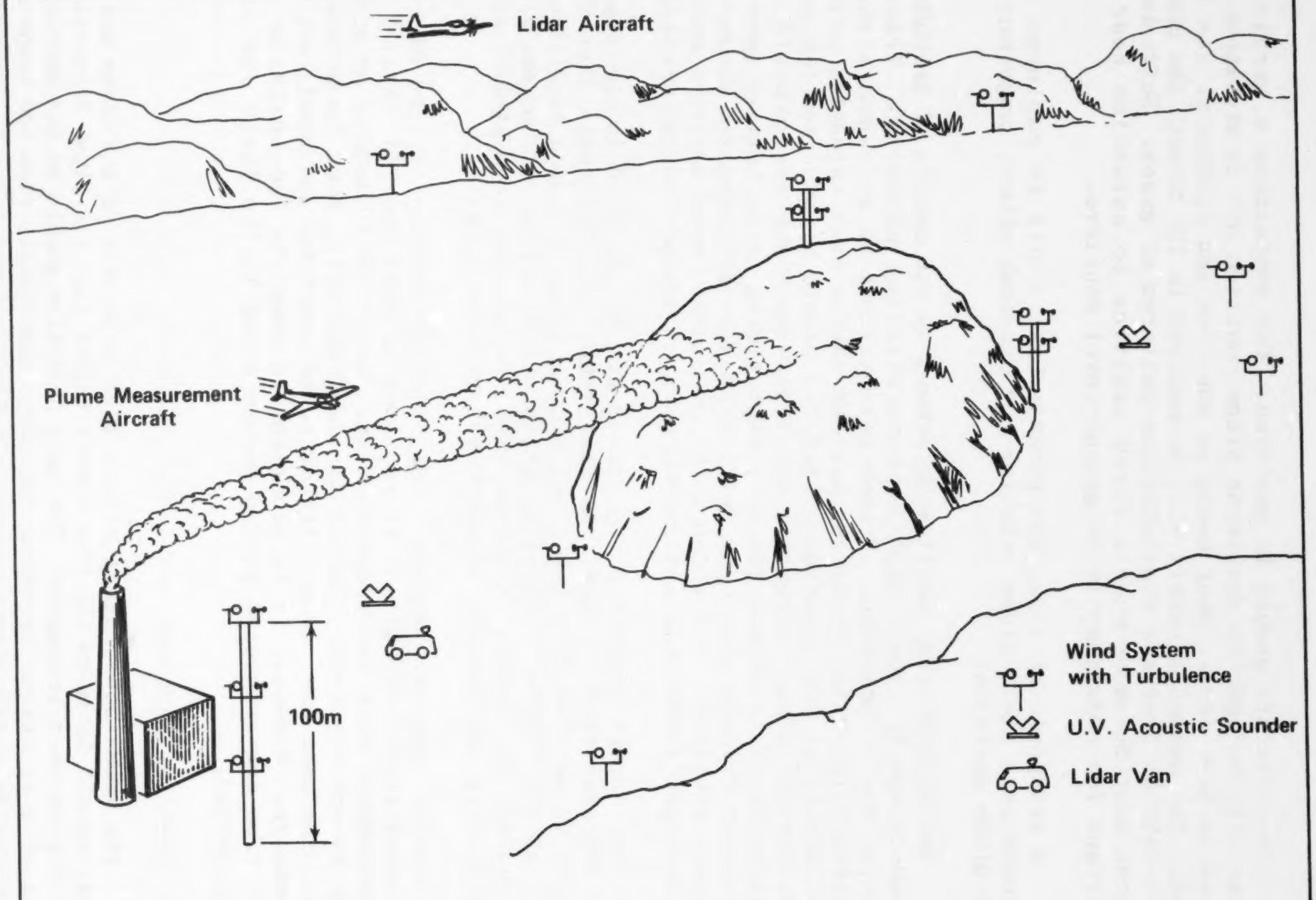
Lidar Aircraft
Plume Measurement Aircraft
100m
Wind System with Turbulence
U.V. Acoustic Sounder
Lidar Van

Figure 4. Perspective sketch of field program.

Two aircraft should be employed. One containing a particle lidar will be used to determine plume position out to distances of 50 km or more for as many hours as the crew and equipment can be used. The second aircraft will be employed to fly through the plume to establish free air concentration patterns of gases. Sufficient passes must be made over a fixed position to establish hourly averages for relationship to ground-level monitors.

A ground-level lidar and perhaps DIAL could be employed to examine near field plume behavior for downwash effect, trajectories and plume position.

The ground-level monitoring network is not capable of providing adequate spatial resolution of concentration patterns. Tracer studies are recommended. Tracer material may be released either continuously or for specified periods during each intensive period and sampled at 200 locations. Samples should be collected for one-hour periods each. Currently available samplers are capable of collecting 12 to 24 samples on preset timing using battery power. Suggested tracers are SF_6 or perfluorocarbons utilizing gas chromatographic analysis. A few (up to 5) continuous tracer monitors should be employed to provide a time history of tracer concentration.

One member suggested the tracer not be injected in the stack but released from a tower. Another member felt strongly that the tracer be emitted from the stack because plume rise is a significant part of the problem. An alternative of using both methods was also suggested; the latter (tower release) being used to systematically investigate the effects of different release heights.

5.3.3 Analysis Timing. Real time collection of some of the meteorological information is required to plan special intensive measurements such as tracer studies. Real time collection of other data is not required. Unlike the isolated hill, fast turnaround, i.e., the next day, is not likely to be available and should not be necessary. However, it is important to complete the analysis of data from one intensive period before going to the field for the next period.

5.4 Model Development

The model development effort that is a part of the large scale study should focus on the flow fields rather than the plume dispersion and impingement processes. The main objective should be the development of a technique by which the three-dimensional flow and temperature fields within the atmosphere's first kilometer can be described quantitatively given the geostrophic flow conditions, the specifications of the local topography, cloud cover, etc. Flow and temperature information is required to model plume rise, dispersion, and centerline trajectory; the Froude number of hills in the plume's path (needed to make concentration estimates on the hill); and, perhaps most importantly, the annual frequency with which plume impaction on particular terrain features is likely to occur.

Flow models of several types should be developed. Physical models should be developed for the terrain site investigated in the field and its simulated flow and temperature fields compared with those actually observed. A demonstration that physical models provide reliable simulations of the microscale flow regime characteristics in complex terrain would help make this type of model a credible source of flow data for other sites.

Numerical flow models should also be developed. A number of "linearized" models currently exist that could be validated or perhaps refined using the meteorological data gathered during the large scale field study. If these simple models prove to be inadequate, far more advanced (nonlinear) numerical models should be developed. In this case a constraint on the model design must be that the computer time and memory requirements be small enough that the model can run on machines accessible to a majority of potential users.

Finally, simple empirical models can be developed that would provide for given geostrophic flow and topography specification (for example, valley depth, width, length, etc.), estimates of drainage flow speed, stability and depth; vertical profiles, wind speed and direction over the valley floor, etc. This model would be used to provide information for plume rise and spread estimates and frequency of occurrence of given plume trajectories.

In addition to the flow field modeling, part of the effort of the large scale study should be devoted to the development of plume rise and spread models that are applicable to complex terrain environments where extreme variations in wind direction and speed and temperature can occur in the vertical. Two-particle, Monte Carlo type models are the simplist models that are best suited for this purpose. The same model can also simulate the plume centerline trajectory and spread given the 3-D flow and temperature fields and information on the flow meander frequency and intensity.

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2. MODEL EVALUATION AND APPLICATION PANEL

PANEL LEADER: Maynard E. Smith

PARTICIPANTS

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Donald Henderson	William H. Snyder

1. INTRODUCTION AND OBJECTIVES

Our panel reviewed the stated objectives and priorities of the EPA group, and attempted to adapt its discussions to respond to the Agency's needs. As we understand them, the objectives are:

A. To establish as accurately as possible the maximum concentrations found when a stable plume impinges directly on a local terrain obstacle.

B. To determine whether the diffusion or distortion of the stable plume differs from that over flat terrain prior to its intersection with the terrain.

C. To consider what input data would be required to make use of new or altered models developed for evaluating such conditions.

Because our panel was expected to address the question of applications, we tried to keep the regulatory aspects of the problem in mind during our deliberation. For this reason, we would require the contractor to relate the experiments to the National Air Quality Standards or PSD increments.

To implement these objectives and meet our responsibilities with respect to the evaluation and application functions, we established an outline of discussions which included:

A. A set of end products or desired results of the studies.

B. Consideration of the role of modeling within the experimental studies and in the application of the results.

C. Consideration of the specific field experiments needed.

D. The evaluation of the field data.

E. The application of the results to regulatory problems.

F. Additional topics which we believe EPA should consider with respect to complex terrain and modeling.

2. END PRODUCTS

As stated in the Workshop "strawman", the air quality modeling system is being designed "to produce atmospheric dispersion models that are applicable to large sources in complex terrain and that have a demonstrated higher degree of reliability than existing models". This basic objective outlines the major end product expected from the modeling program. This end product will be the result of either the refinement of existing Gaussian models or the development of new models embodying advanced techniques and using the data base collected during the field experiments.

In order to accomplish the study objectives, and to allow proper interpretation of results for regulatory application, it is necessary to determine the wind, turbulence, and concentration fields as functions of both time and space.

In terms of time resolution, a required end product is to obtain concentration measurements for averaging periods ranging from ten minutes or less to as long as three hours. Consideration of this time range will permit the interpretation and proper extension of modeling results to be compatible with applicable standards. These time average specifications should, to the extent feasible, be augmented by continuous concentration measurements to provide an accurate characterization of the fine-scale structure of the three dimensional wind, turbulence, and concentration fields. In addition, a methodology must be developed for assessing plume impacts up to a twenty-four hour averaging period.

In terms of the spatial scale to be examined, strong emphasis should be placed on developing the modeling capability for describing near-field impacts, i.e., source-terrain separation distances ranging up to several kilometers. Consideration of long-range transport, and its associated problems, should not be within the scope of these impingement experiments.

An additional and very important end product of the study should be an assessment of the transfer value of the experimental results to other locations.

We believe that this project should include the following:

A. Specific evaluation of presently used "off-the-shelf" models with inclusion of confidence limits.

B. Delineation of model applicability and limitations of modeling results.

C. Specification of minimum meteorology and source input data necessary to provide reliabile impact estimates.

D. Determination of the concentration probability distributions of the test data.

E. Examination of the meteorological conditions likely to cause the highest second-highest limiting concentrations in complex terrain for the three-hour and twenty-four hour averaging periods.

F. Recommendations for further research efforts to extend the results of this study to other terrain configurations and time-averaging periods.

3. MODELS

The details of the models that will evolve from these plume impingement studies cannot be specified a priori. However, there are certain model features and modeling criteria that should be addressed prior to the experimental design to insure the adequacy of the design and to facilitate the application of the results to real sources. We believe that it is very important to develop at the outset a model construct that contains, in as much detail as possible, all of the basic terms and parameters that will be required to analyze the measurements obtained during the experimental program. It should also provide for the generalization of the modeling techniques developed from the experimental data, so that these techniques can be applied to specific sources and terrain situations.

The basic model construct should include characterization of the following:

A. Source

B. Stable Approach Flow

C. Plume Characteristics Prior to Impingement

D. Impingement

E. Hill Surface Boundary Layers

F. Ground-Level Concentrations

G. Time Averaging

A prototype model construct containing these factors should be developed and used to calculate expected ground-level concentration patterns for various combinations of stability, aspect ratio, wind speed, Froude number and other critical parameters for the experimental terrain factors. One should also remember that various hypotheses may apply, and a single model construct may not be sufficient.

The importance of the prototype model construct and calculations is that they will force specification of source, meteorological, terrain, and flow parameters that control the various processes, and provide an objective framework for experimental design, data analysis, and model development.

4. SPECIFIC EXPERIMENTS

Our panel decided that two field experiments are desirable, one on a relatively small scale and the other on the scale of a major terrain obstacle. The first at least should be replicated in a fluid modeling facility.

It is important that flow visualization should be conducted before either sampling network is made final. Such tests would insure appropriate placement of the sampling equipment, and might provide valuable information on the diffusion, aerodynamic and transfer processes as well.

Real-time measurements of the meteorological variables, and some of the key concentration measurements, would be helpful in managing the experiments, but much of the concentration data need not be immediately available.

4.1 Small Scale

Partly because of concern about extrapolating the results of a small-scale experiment to very large terrain features, and partly because of the interchange of ideas with other panels, we debated the relative merits of 100 m versus 400 m hill experiments at length. The conclusion was that the 100 m experiment was a better choice for numerous reasons, the primary ones being that (a) the work would be easier to accomplish, (b) it appeared to have a much greater chance for success in illustrating, measuring, and understanding the physical mechanisms involved in the transport and diffusion of pollutants through the atmosphere to the hill surface. We had no objection to a larger hill experiment if all equivalent measurements were made.

The panel also debated the relative merits of the 100 m hill (Snyder) versus the 25 m hill (Lamb) experiments. The latter appeared overly complicated and was likely to be too often submerged within the turbulent surface layer under very stable flow conditions. A natural 100 m hill would extend above the turbulent surface layer much more often, and it was our first choice.

The details of the experiment received considerable attention, especially with respect to measurements which would insure physical understanding of the mechanisms involved. We recommend:

A. Meteorological Measurements. Wind speed and direction, temperature, and three components of turbulence intensity up to at least 1.5 times the hill height on each of the main towers: these data to be logged for the duration of the study periods (twenty-four hours per day for three to six months) not just during tracer release periods.

B. Concentration Measurements. A sufficiently dense network of samplers on the hill surface as well as a few above the shallow (turbulent?) surface layer would show whether there may be sharp concentration gradients near the hill surface because of stagnation, a turbulent surface layer, or katabatic winds. It would also help in understanding of the key processes involved in the transfer of pollutants from the laminar approach flow to the surface itself.

C. Hill Surface Layer Measurements. Attempts should be made, preferably through relatively simple means (possibly smoke releases, smoke rockets, wool-tuft grids, etc.), to determine the main characteristics of the surface layer on the hill, i.e., its depth, speed, and direction over the entire surface of the hill.

D. Source Placement. The placement of the source, vertically and horizontally, is very important, especially since the stable plume is likely to be exceedingly thin in the vertical. Indeed, upon further discussion, it was deemed essential to "fatten" the source artificially. The tracer could be released through rakes of small tubes distributed in the vertical and horizontal directions to obtain expanded initial plume dimensions, σ_{zo} and σ_{yo}.

E. Averaging Times. It is recommended that the source be fixed during a given test period (three hours) and that the concentration measurements be made (in segments not to exceed ten minutes) during the full three-hour period. The panel felt that averaging times of ten minutes or less were essential in order to understand the physical mechanisms involved (e.g., so that a "plume-meander factor" can be determined), but it was concerned about possible misapplications or extrapolations from ten-minutes to three-hour averaging times.

F. Hill Shape. A hill, ellipitical in plan view with an aspect ratio of approximately 3:1, is preferred. Early investigations of wind distributions and smoke plume visualizations are recommended to insure that the winds frequently blow in a direction nearly perpendicular to the major axis of the ellipse.

G. Synoptic Data. While synoptic data are believed to be unnecessary for the conduct of the small scale experiments, they may become valuable in specifying model input data or in transferring the results to other terrain features. We therefore recommend that they be obtained at the time of the tests and included in the data package.

4.2 Large Scale

The basic types of meteorological and concentration measurements required for the small scale experiment are also required for the large scale experiment. The criteria, with respect to the terrain geometry and the expected frequency of stable flow in the direction of the terrain, are in principle the same for both scales. The large scale experiment offers a choice of sources, a real source (power-plant stack plume) or a simulated source (tracer). The use of a real source has the advantage of incorporating source characteristics that must be ultimately included in model applications, such as plume buoyancy. On the other hand, plume buoyancy is not directly related to the impingement process, except as it relates to the effective source height and the dimensions of the experiment. Therefore, the disadvantages of using a real source are that the source strength, effective source height, and source location with respect to terrain cannot be controlled.

The use of a tracer allows a greater degree of control and flexibility and may also be desirable for other reasons (e.g., simplification of concentration measurements). The tracer source is therefore our recommendation.

The large scale experiment also introduces complexities, with respect to the structure of the flow in the stable layer and the boundary layer, that are not present in the small scale experiment. Characterization of these flow patterns may therefore be more difficult.

Without considering the constraints that may be imposed by logistical, budgetary, and measurement factors, the large scale experiment probably should not be carried out until the small scale experiment has been completed. This would allow for testing of the basic concepts involved in the terrain impingement process and the development of parameterization criteria.

It is recommended that the meteorological data be collected and summarized (hourly) for at least a one-year period at the site.

Again, the terrain features of the large scale study should be selected so that there is a reasonable frequency with which the plume centerline will impinge directly on the terrain feature. This may postpone experiments on very large two-dimensinal terrain features (ridges) until comprehensive studies of large hills are completed.

5. EVALUATION

It is most important that the sufficient funds be allocated to insure that the experimental work and the model development are evaluated fully after they are completed.

5.1 Matrix of Tests

A matrix of meteorological, source, and receptor conditions should be chosen to be sure that the processes are described adequately. For example, in the small scale experiment, one might decide upon a minimum of three wind speed groups, three delta-temperature classes, three source heights, and two approach angles.

5.2 Repetitive Tests

Within each box of the matrix one would want more than one field test in order to establish confidence limits of the result. It is our opinion that approximately six to ten tests in each box would be desirable.

5.3 Data Retrieval

It would be very helpful if most of the concentration data could be reduced and carefully inspected within 24 hours. This would permit a quick review and increase the efficiency of the test program. However, the key meteorological data and selected portions of the concentration data should be available in real time to facilitate handling of the individual experiments.

5.4 Statistical Analyses

We recommend that EPA define a minimum set of statistical analyses needed to establish the adequacy of the model performance.

5.5 Sensitivity Analysis

The model resulting from the study should be subjected to a sensitivity analysis to insure that it will produce reasonable results over the full range of intended applications.

5.6 Comparison with Existing Field Data

While we recognize that there are few sets of field data suitable for comparison with the new (altered) model, a serious attempt to match model predictions with such data should be attempted.

5.7 Independent Evaluation

Because of the complexity of both the problem and the experiments, we recommend that EPA arrange for an independent, concurrent review and evaluation of the program. We do not mean quality assurance of the data, for that is a separate problem, but rather, review of the overall technical quality of the program.

5.8 Data

In conjunction with (5.7) it is most important that the entire set of field data be taken, reduced, and described in such a way as to permit independent evaluation.

6. APPLICATIONS

The contractor should prepare a technical document which fully describes the experiment, the data, and the model development. In the interests of assuring proper use of any model, it is also necessary to list limitations, special conditions, and confidence bands for those using the model.

Because this study is designed specifically to define plume impingement on elevated terrain, the results may not be applicable or transferable to all complex terrain situations. Therefore, the degree of flexibility in the model application should be described. Flexibility in the model use is dependent on the skill of the user in relating the measured flow patterns to the wind tunnel and tank studies and in extrapolating the results to other source-terrain configurations.

Potential limitations are:

A. Near-field application, approximately one hour travel time.

B. A source-terrain configurataion similar to that upon which the model is based.

C. Restriction to those meteorological conditions which existed during the tests.

The input data developed by the user must be compatible with the model requirements. These data cannot be specified until the final stages of model documentation, but it seems clear that certain measurements will be required regardless of the type of model that evolves. These are:

A. Onsite measurements of wind speed, direction, and stability in the layers that affect plume transport and dispersion. These data must be consistent with the averaging time of the model.

B. Necessary meteorological and source input data which will permit the user to convert from the model averaging period to longer-term averages for direct comparison with regulatory requirements.

C. Emission parameters.

D. Definition of the terrain.

The funding required for even the "minimal" requirements cited above will be beyond the financial capabilities of some applicants. Such applicants should be guided as to the acceptability of meteorological data from beyond the environs of the pollutant source. A first step toward such guidelines could evolve from a study of the applicability of the experimental data obtained at various sites during the field tests. The support document for such guidelines should include discussion of the degradation of model results in terms of the degradation of the input data.

7. SUGGESTED ADDITIONAL STUDIES AND ISSUES

7.1 Non-Impingement Maximums

The maximum three-hour concentrations in complex terrain often are not associated with the direct impingement of stable plumes on high terrain obstacles. Rather, the maximum values are frequently found during transitional periods when the stable plumes are brought close to valley walls by thermally-induced circulations generated by unequal heating and cooling of major terrain features. Such phenomenon may occur, for example, when the western wall of a valley is heated by the sun in the early morning while the eastern wall is still in the shadow; a cross-valley circulation develops, causing a transitory fumigation situation.

Another situation which should not be ignored is the extremely persistent moderate to strong wind neutral condition. This situation may be more important than the stable case in producing 24-hour maximum values in some configurations.

We recommend that EPA investigate these phenomena, using the experimental data generated in this project, as well as other available records.

7.2 Relation to National Air Quality Standards

Even after completion of these studies, few of our panel members expect the predictions of the highest second-highest concentrations at locations different from the test sites to be accurate within a factor of two. Factors of three to ten are more likely.

An important reason for this large uncertainty factor is that the meteorologists are being asked to predict an extreme value in the probability distribution of concentrations. As Lamb points out in his written comments on this program, the highest second-highest concentration is extremely difficult to predict. Grey, in his letter to Hovind dated June 22, 1979, also recognizes this problem, but neither he nor Lamb suggests one obvious solution; the meteorologists could very well insist that the quantity which they are asked to predict be a reasonable one.

The highest second-highest concentration is an administrative choice reflecting the idea that there are certain maximum concentration levels below which health and welfare effects are insignificant. These same maximums could easily be achieved in most cases by relating them to a reference concentration in the probability distribution which occurs much more frequently than the highest second-highest value. A more predictable quantity would make our regulatory decisions less capricious. It makes little sense to insist that the emission limitation for an industrial plant be twice as stringent if based on one set of five-year meteorological records than it would be if based on a different five-year set. As one member of our panel asked: "If the predicted 3-hour highest second-highest SO_2 concentration for a given plant is 1,420 g/m^3 (~10% over the 1,300 g/m^3 standard) and the accuracy of the prediction cannot be specified to better than a factor of five, should we deny him a permit, or require 50 million dollars worth of control equipment?"

The field data needed to readjust the definition of the standards, without changing the desired maximum levels, exists. Judicious use of it would permit us to employ a much more orderly system, based on more predictable values. This does not imply abandoning the intent of the existing standards, such as allowing only rare exceedances of 1,300 and 365 g/m^3 SO_2 concentrations for the 3-hour and 24-hour averaging periods, but rather, achieving them in a better way.

This question is, in a sense, beyond the scope of this Workshop, but it is not beyond the consideration of the accuracy of complex terrain (or any other) model.

3. EXPERIMENTAL DESIGN PANEL

PANEL LEADER: Gene Start

PARTICIPANTS:

Shep Burton	Frank Schiermeier
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Ron Lantz	Dean Wilson
G. DeMarrais	Mike Williams
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1. EXPERIMENTAL DESIGN

1.1 Introduction

A goal of this Workshop is the identification and selection of an important and tractable aspect of the behavior of airborne effluents within the setting of complex terrain. The primary focal point selected for investigation is the concept of plume impaction upon elevated terrain. Plume impaction is the behavior of a plume as it encounters the terrain. Emphasis is directed toward understanding this phenomenon for plumes which are emitted well above the ground and which interact with higher terrain at downwind locations. Uncertainties exist regarding which phenomena are significantly contributing to the plume/terrain interaction and what magnitude of effect will result from the action of these phenomena. There are several possible features of the topographical setting and on-going physical processes which may be important contributors to the cumulative behavior which is termed "impaction". Certain broad categories of terrain and meteorology may be considered and the experimental focus may be selectively reduced to include a subset of them. This subset may be examined more thoroughly than the full set. The qualitative and quantitative understanding developed from the subset would provide sound guidance for understanding these selected conditions and perhaps guide related modeling for the remaining situations not investigated.

It is desirable to investigate impaction as a function of terrain types. Four types of terrain have been identified and ranked in order of expected complexity. They are 1) isolated hill, 2) ridge line, 3) broad valley, and 4) canyon. The isolated hill appears to be the simplest, most easily understood topography and the study of it is recommended to be first. It also is the easiest to compare to concurrent wind tunnel and water tank simulations. Subsequent studies should consider the other topography once understanding (some of which should be transferable) is developed for hills.

Impaction needs to be studied as a function of meteorology. Three atmospheric stability situations are considered most important; stable, neutral, and transitional from stable to neutral conditions. Unstable stabilities should also be investigated, but stable flow is the selected focus of this Workshop due to its greater importance in current modeling evaluations. Neutral cases also have significant potential for impaction of high concentrations on elevated terrain. Such impacts have been observed and documented.

The transitional period from stable to neutral flow is included because it presents a potential for mixing very high concentrations to the surface of elevated terrain. Studies of plumes originating during stable conditions, with airflows over elevated terrain, may include impaction during transitional periods (either a diurnal change or a turbulent episode) and thereby provide insight on other features of the impaction process.

The evaluation of plume impaction upon complex terrain must include many considerations in order to achieve probable success. The experiment must include surface and upwind aerial measurements of tracer concentrations. Central to the experimental design is the need to discern how the tracer concentrations measured on the terrain slopes compare to the aerial tracer concentration which would have existed at the point in space were there no topographic features. The essential ideas are summarized in Figure 5. Several observations of plume centerline concentration must be collected at distances upwind of the terrain in order to unambiguously specify the magnitude of tracer concentration and the rate of change of concentration with downwind distance. These observations must yield an extrapolation (or projection) of expected aerial concentration for the distance of the elevated terrain. A corresponding observation of tracer concentration on the slope is measured. The ratio of observed to expected (extrapolated) concentration is termed the impaction ratio. If the ratio equals one, the terrain obstacle presents no detectable alteration of plume concentration and complete or full-value plume impaction has occured; if the ratio equals 0.1 the impacting plume concentration is only 1/10 of expectations and some diluting or resisting mechanism has reduced the magnitude of the plume impaction. It is very important that the same averaging times be used for all tracer concentration prior to ratioing them.

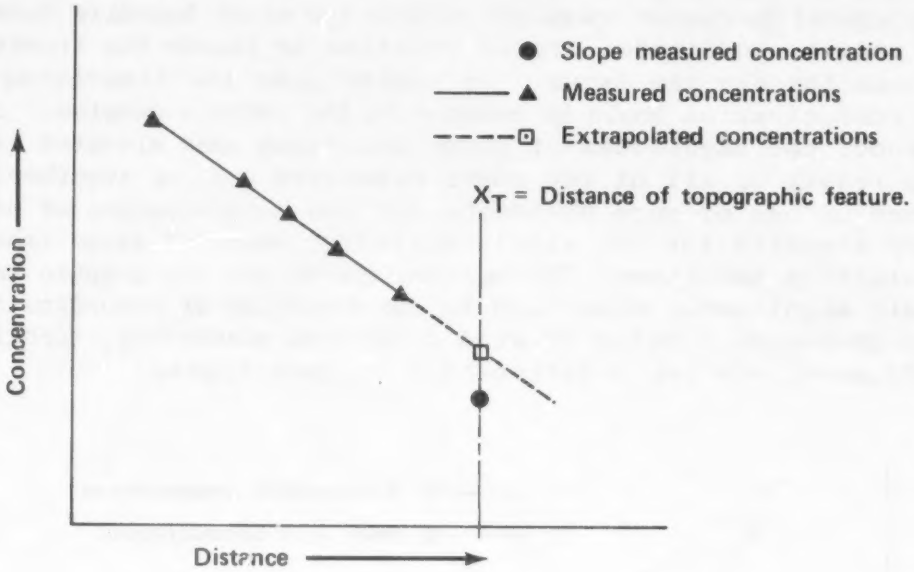


Figure 5. Estimation of ambient plume behavior and the degree of impaction upon elevated terrain.

If the ratio differs significantly from unity, then more detailed measurements of magnitudes and profiles of micrometeorological and tracer concentrations would be useful to understand the near terrain slope processes which alter these plume impactions. Figure 6 schematically depicts a possible observed near-slope profile of tracer concentration and an extrapolated profile of tracer based upon upwind measurements. A divergence of these profiles from one another is depicted. Two hypotheses for the differences in concentration profiles are the following. The average observed tracer concentration values (and therefore the profiles) are less than expected because of topographically induced transport and/or diffusion effects. These time integrated (averaged) concentrations could be less, due to the tracer samples being collected during alternating periods with full-value and reduced-value (or even tracer free air) concentrations. Under this situation, the tracer concentrations in time integrated samples collected on the slopes would be less than the extrapolated tracer concentrations; but the area of coverage on the slopes could be larger than expected from extrapolations of the plume cross-sectional area determined at upwind points of observation if enhanced meandering of the plume centerline occurs near the topography. Another manner in which smaller concentrations might be sampled on the terrain could be the result of the slope boundary layer (when it exists). The micrometeorological processes operative within the slope boundary layer may either produce additional tracer dilution or impede the transfer of plume mass through the layer. In either case the time-integrated tracer concentration would be reduced in the terrain samples. In all likelihood, the magnitudes of plume impactions upon elevated terrain are the result of all of the above processes acting together. The dominance of one or more phenomena (or the subordination of others) probably accounts for the widely differing observed plume impaction and postulated behaviors. The meteorological and topographic factors and their magnitudes, which lead to the dominance or subordination of certain phenomena related to wind direction meandering, turbulence, and diffusion, are key relationships to investigate.

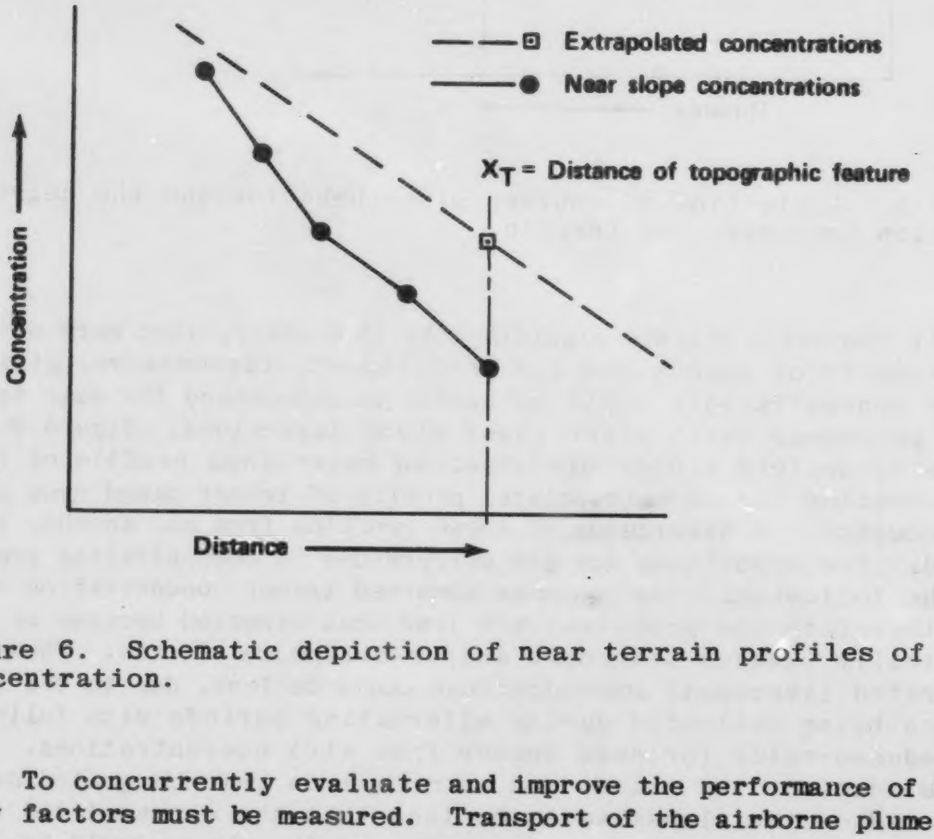


Figure 6. Schematic depiction of near terrain profiles of tracer concentration.

To concurrently evaluate and improve the performance of models, many factors must be measured. Transport of the airborne plume may be a highly important factor and it is recommended that winds be determined in the form of a multilevel field of u, v, w wind speed components. The dispersive power of the atmosphere should be parameterized for each test through the measurements of turbulence, ambient plume diffusion and atmospheric stability. Parameters describing the tracer sources, such as its strength, height and horizontal location must also be documented. An effort to establish the energy budget (e.g., various turbulent fluxes) might also be included in the experimental measurements.

The conduct of the experimental study may be significantly affected by practical constraints. The most important constraint could be the funding limits. The design and budget should be carefully prepared to ensure that the most imporant parameters are being included and that the experiment isn't too limited in scope to provide sufficient information to obtain meaningful results. The design also must consider the availability of potential sites which satisfy the experimental requirements. One type of idealized measurement site would have a power plant about 5 km upwind of an ellipsoidal hill which extends higher than the effective plume height; transport of the plume, during stable flow, would occur toward the hill 365 days per year. It is doubtful that such a site exists. Therefore, the experimental design must consider availability of sites early in the design process.

The experimental design must consider the timeliness and the applicability of the results. Some findings (significant information) should be provided after a reasonably short period of time in order to demonstrate the desirability of continued funding of this program. The information acquired must be applicable to the real world and have direct relevance to the engineering design and regulatory problems of plant settings within complex terrain. The selection of a "full-scale" setting (typical of a number of operating fossil-fueled power plants and/or smelter plants) should be considered.

A real concern is the risk of developing erroneous conclusions due to an inadvertent (and unknowing) subordination of certain physical processes. These physical processes, because of the selection of smaller than typical settings and topographic features, may have an inordinately small relative contribution to the overall combined effect by the full spectrum of transport and diffusion mechanisms. If the relative contribution of a phenomenon to the transporting and/or diffusion of an airborne effluent is scale dependent, then conclusions based upon observations at a small hill may not translate to conclusions for a large hill, etc. For example, the presence or absence and size or magnitude of the effects of slope flows and slope boundary layers are believed to depend upon terrain obstacle size. The ultimate transfer of airborne material to the terrain obstacle surface (plume impaction) can be significantly altered by the strength and size of slope boundary layers and flows. If a choice of scale for the field study excludes or subordinates these phenomena, there is a distinct risk that inapplicable conclusions (and formulated models) would be applied to larger settings in which these phenomena would contribute significantly. On the other hand, investigations of a specific setting will increase understanding of that scale; a second investigation of a substantially different scale will provide additional understanding. There may be partial agreement between study findings and some distinctly different and perhaps conflicting findings for studies of very different size of topographic features.

Some other constraints will be in the areas of instrumentation and expertise to handle the job. The measurement and design panels jointly attempt to avoid the development of a plan for which no adequate and proven instrumentation or methodology exists, or whose implementation would be prohibitively expensive. Similarly, the availability of qualified contractors must be considered when establishing a time table for the experiment. (They may already be committed to another activity).

From an advancement of science perspective, it seems desirable to study the simple geometry and setting to gain a clear understanding of the observed plume behaviors. This understanding may be a transferable module which is incorporated (largely intact) into either more generalized models to be developed or used as a module for adjusting some of the existing models to plume transport, diffusion, and impact. Once an initial understanding is achieved, the more difficult and diverse settings and processes may be examined through module by module systematic investigations, as necessary.

The advantages and disadvantages of three scales of complex terrain plume studies were considered. The scales are (1) small (50 to 100 m high) hill study, (2) power plant scale plume study, and (3) large scale (400-600 m high) hill study. Preliminary scenarios for scales (1) and (2) are contained in Appendix A. A summary of strengths and weaknesses for each scale of study follows.

3.1.1 Small Scale (50 to 100 m) Hill Study

- Advantages. Source mobility is a decided advantage over a fixed source in guaranteeing plume impaction of the hill under study. The logistics of conducting such a small scale tracer study are decidedly easier than either of the two larger scale studies.

Because of the small scale, this study has a closer relationship to laboratory or physical plume modeling. The relatively low plume heights would permit experiments to be conducted in the most stable regimes which occur close to the ground surface.

- Disadvantages. The small scale of this study poses several measurement problems (for example, plumes are of small size and travel distances are relatively short) because measurements of particulate plumes by lidar would be approaching or decreasing below the lower limits of resolution. To alleviate this problem it has been proposed to develop an initial volumetric source or to relocate the source farther upwind. This tradeoff may permit improved lidar resolution, but would increase the difficulty of aiming (impacting) the plume on the small hill target; the releasing of tracer with a virtual size would also be more difficult.

Even if lidar measurements of the particulate (e.g., oil fog) plume were made possible by this adjustment, the determination of absolute concentrations of plume tracer remains a difficult problem. Airborne detection systems for tracer concentrations would be ineffective in measuring axial values due to the small vertical extent of the plume. Also, aerial sampling may significantly affect the small plumes by the additional turbulence due to the aircraft. Balloon-borne measurement packages may yield vertical plume dimensions but appear to be unworkable due to a likelihood of horizontal positioning errors.

The preliminary proposal (Snyder, Appendix A) using five 150 m instrumented towers, is believed to be too costly. When these costs are combined with other direct study expenditures, they are estimated to about 75% of the $3.3 million tentatively allotted for the field experiments. A subsequent proposal to reduce the tower requirement to one 100 m tower eliminates the cost problem, but significantly cripples the information content of the small scale study. To sample the low-level wind fields near the obstruction, it may be necessary to revert to low resolution pibals since remote sensors such as acoustic dopplers cannot measure within the initial 30 to 60 m above the ground-surface.

Finally, the appropriateness of the scaling of the small scale study to the real world situation can be a problem. Phenomena such as wind shears, strengths of the boundary layer, and the size of mechanical/convective eddies are necessarily different between the proposed small scale and the larger scale in which power plant plumes disperse.

- Conclusion. The panel feels that the small scale hill study consists of many valuable experimental concepts, but that the scale is probably too small to be workable, clearly representative, or of immediate applicability. Therefore, these concepts have been embodied into a large scale hill study.

3.1.2 Power Plant Scale Plume Study

- Conclusion. Without describing the advantages and disadvantages, this option was passed over because of its dependence on power plant emissions from a fixed source location. The occurrence of useful test days in which the wind transport was acceptable might be rare. The funding for the field experiments is too limited to allow success to be dependent on the vagaries of transport wind direction and plant operational characteristics. Ideally, this scale of field study would reflect the real world, but it is not affordable at the anticipated funding level and no suitably situated plant has yet been identified.

3.1.3 Large Scale (about 400-600 m) Hill Study

- Advantages. The basic premise of this tracer study is to incorporate the source mobility of the small scale hill study, but project it toward a larger terrain obstacle in an attempt to facilitate supporting measurements. For example, the upwind fetch is sufficient to permit definitive transport and diffusion measurements of the combined tracer/particulate plume by airborne lidar and tracer-sampling aircraft. Similarly, the plume elevation is sufficient to permit definitive measurements of the plume structure, the boundary layer and the low-level wind fields by remote sensing techniques such as ground-based lidar and acoustic doppler sytems.

More important is the closeness of this scale to real-world situations and the minimizing of concern regarding scale subordination of phenomena affected by wind shear, boundary layer existence and structure, and turbulent diffusivity. This resemblance to actual power plant plume situations and dispersion provides for more immediate applicability of results, and an immediate credibility to non-technical and non-meteorologist recipients.

- Disadvantages. Because of the increased scale, the large scale hill study necessarily entails more logistical difficulties in some ways (but possibly less in others). Although achievable, this study would require more personnel, aircraft platforms, remote sensors, and increased source strength. These additions not withstanding, the large-scale hill study (field experiment) would cost about half as much to the same as the costs for the small scale hill study (as originally proposed).

- Conclusions. It is recommended that at least two large-scale hill studies be conducted in the complex terrain setting. For reasons cited above, this approach is deemed most cost effective, more acceptable and representative, and would produce results of immediate applicability. The conduct of the necessary measurements appears feasible with existing measurement technology.

The small-scale hill study is believed to exceed (or extend to the very limits) the resolution capabilities of most remote and airborne measurement systems. Fixed in-situ measurement techniques are possible but the costs of these measurement arrays to define the meteorology and the plume diffusion adequately are believed to exceed greatly the costs for the large hill measurement configurations.

3.2 Design Concepts for Plume/Terrain Interaction Study

To examine the interaction between airborne effluent plumes and elevated terrain near effective plume height, a setting is desired with the height of the topography comparable to or greater than typical plume heights associated with fossil fueled power plants during stable conditions in the Western United States (to avoid controversy regarding scale size). The experimental design will be discussed from the perspective of the 400-600 m hill.

The work required for this study can be conveniently separated into components associated with site selection, frequency and duration of experiments, and the measurements which must be made in characteristic zones of pollutant behavior.

3.2.1 Site Survey and Selection. An initial task will be selection of an appropriate site or sites which optimize the chance of useful information within budget, time, and design constraints. The design constraints include a 400 to 600 m hill reasonably isolated from major terrain influences by fetches of relatively flat land. In this context, releases may be made at distances of up to 5-10 km from the base of the hill; tracer releases should be initiated at locations free of wake effects from other terrain roughness influences.

The hill should also be relatively symmetrical (circular to elliptical). For circular symmetry, releases may be made from a number of directions without changing the cross-sectional shape of the terrain; for elliptical symmetry the contribution of aspect ratio might be considered. The intent of the circular symmetry constraints is to provide many similar stable flow experiments with features as consistent as possible during study periods. Some of these constraints on symmetry of the hill could be relaxed if certain wind directions are precluded because of inappropriate upwind terrain. Also, if crosswind shape variation does not significantly detract from the measurements or does not diminish the number of acceptable testing days which occur, or if aspect ratio does not significantly detract from the measurements or does not diminish the number of acceptable testing days which occur, or if aspect ratio variations are desired, hill symmetry becomes less important.

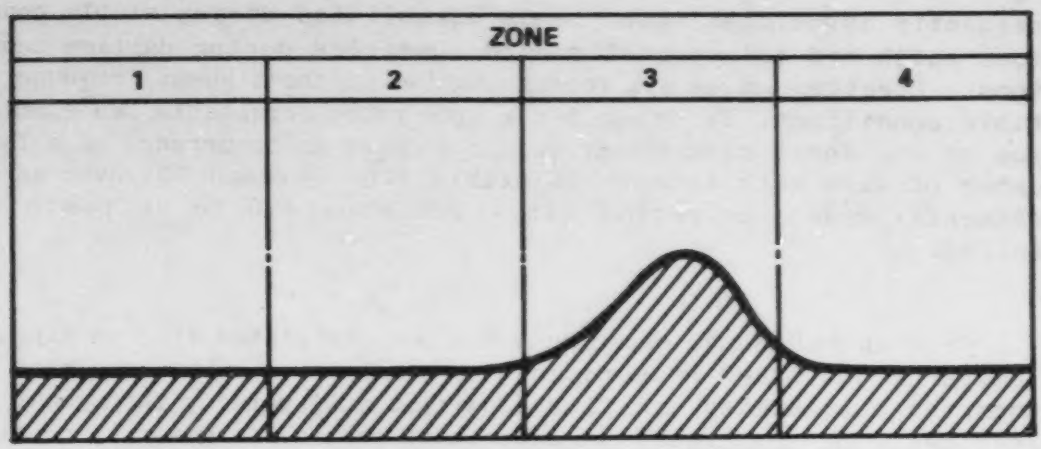
An important consideration, although not essential, would be the possibility that a given site (hill) may be situated within a region of channeled flow so that the frequency of acceptable testing conditions is greatly increased along certain preferred wind directions. Then the logistics could be greatly simplified because appropriate source release points and fixed measurement sites would be much easier to locate, and more permanent.

3.2.2 Frequency and Duration of Experiments. An important requirement of the site is a high frequency of stable flow with depths up to and exceeding the height of the hill.

A goal is to achieve 50 stable flow experiments (total) during conditions of stable flow over two periods of testing. Each experiment should include at least 3 hours of tracer releases and measurements, and 6 hours is suggested as a usual duration. (Impaction contributions to the 3 hour air quality standard are to be considered). The experimental periods would cover two or more seasons of the year during which stable conditions are expected. A relatively large number of experiments is required in order to provide information on the details of plume interaction with high terrain considering variations of wind speed, temperature gradient, height of release, and time of day. In the case of time of day, nighttime and morning cases may be of special interest. Morning cases are important. Field experience indicates that the occurrence of high concentrations upon elevated terrain is frequently associated with plumes established during stable conditions which are transported toward obstacles during daytime conditions. Nighttime cases are representative of the highest frequency of stable conditions. In order for a site to be acceptable, an examination of the local climatology should suggest an occurrence of a large number of days with acceptable stable flow (exceed 30) over an experimental season or period (in which about 20 to 25 tests are desired).

Once an individual experiment has been initiated (for an expected 6 hours of continued measurements), there is no assurance that the atmospheric stability and flow condition will persist throughout the experiment. In this event, the experiment should, in general, continue since important transient behaviors and understanding of peak to average concentration fluctuations may be documented.

3.2.3 Characteristic Zones. It is convenient to describe the experimental measurements from a concept of charateristic zones within which certain activities and changes in turbulent diffusion and plume transport are expected. Four zones are identified and are shown in Figure 7. Zone 1 contains the release of the tracer plume (and its plume rise, stabilizations, etc., if applicable). Zone 2 is the transport zone. Within Zone 2 the tracer plume is transported and diffused by usual atmospheric conditions (those conditions not incorporating topographical distortions of flow streamlines or alterations of turbulence). The "ambient" behavior of the plume is established in this zone. Zone 3 contains the terrain feature of interest. This terrain feature is instrumented to measure possible plume impaction upon the slopes; airflow distortions, changes in atmospheric turbulence, and differing rates of diffusion developed here. Zone 4 is the region "downwind" of the terrain feature. Within the wake zone the tracer plume continues to be transported and diffused in manners which differ from the ambient conditions of Zone 2. However, at longer distances downwind, Zone 4 transport and diffusion characteristics converge toward the Zone 2 ambient conditions. Each of the characteristic zones and the measurements to be performed are described in greater detail in following paragraphs.



Zone 1. Tracer source (plume stabilization, etc. as appropriate).
Zone 2. "Ambient" transport and diffusion during approach to elevated terrain.
Zone 3. Plume interaction/impaction with elevated terrain.
Zone 4. Downwind wake transport/diffusion/impact and return toward ambient conditions.

Figure 7. Conceptual depiction of characteristic zones of tracer plume transport and diffusion.

- Source Zone (1). The principal activities required in the source zone are the release of gaseous tracer and a particulate tracer. The particulate tracer should be suitable for providing flow visualization (probably via airborne lidar) at distances beyond 5 to 10 kilometers. The release platform for the particulate and gaseous tracers must be semi-mobile, with capacity for six to seven hour duration of tracer release. The source height should be adjustable so the plume height can be varied from about half-hill height to a modest amount higher than the hill top. The horizontal location of the source should be semi-mobile (unless the ideal site was found) so that it may be easily positioned directly upwind of the hill before the experiment is begun. Once the experiment is begun the source will be fixed for the full test period (6 hours). The effective initial size of the plume shall be on the order of 30 to 50 m in the vertical and 75 m in width. These minimum dimensions ensure that known plume sampling methodology may be effectively utilized to define plume spread statistics, concentrations, and spatial locations within Zone 2 prior to interaction with the elevated terrain. Particulate tracer and gaseous tracer plumes must be coincident downwind of the release point(s).

The use of multiple release points for pairs of separately identifiable particulate and gaseous tracers could provide greater assurance that a successful test was achieved during each attempt. A method of distinguishing between the various particulate releases might be required so that flow visualization advantages could still be retained.

- Transport Zone (2). This zone of meteorological transport and turbulent diffusion is of nearly equal importance to the actual high terrain zone of plume influence (Zone 3). Within this zone the atmospheric rate of diffusion, which determines the upper limit magnitude of plume concentration which potentially may reach the slopes, is operative. Since neither this rate of diffusion nor the absolute concentration can be predicted with precision, the concentration at a number of successive downwind distances must be measured; uncertainties in the absolute concentrations will translate directly into uncertainties in the degree of impaction of plume centerline concentration.

Documentation of plume transport winds and the observed trajectories will yield insight regarding peak to average tracer concentration statistics and the frequency of occurrence of transport to the terrain object in question. It is very important that the measurements in Zone 2 are sufficiently numerous so that the details of plume dilution can be defined before the terrain begins to perturb the flow and plume concentration. Otherwise, it will be impossible to estabish what additional dilution results from terrain interactions. In addition, measurements within Zone 2 will be related to long-term on-site measurements in order to define the frequency of terrain interaction in a climatological sense.

There are two major types of information to be observed in Zone 2: (1) plume characteristics and (2) meteorological characteristics. Plume characteristics will be defined in two ways. First, the spatial distribution of the particulate tracer will be examined by airborne and ground-based lidars. The airborne lidar will provide cross-sections of the plume at various distances downwind from the source. These measurements will extend into Zone 3, and possibly farther downwind. The airborne lidar system would provide plume transport depictions and structure in this zone and in Zones 3 and 4 as well. The ground based lidar will provide multiple planes of observation of the plume in a nearly instantaneous sense. A pooling of these observations will yield averaged time histories of concentration (relative) and plume spreading statistics. A minimum of two, and preferably 3 to 5 planes (lateral-vertical) of observation are needed.

In addition to the particulate tracer observations, an airborne system must sample the nearly instantaneous plume centerline maximum concentration of the gaseous tracer by traverses through the plume. These samples must be at locations which correspond to the cross-sections of particulate tracer observations so that the particulate plume (which may be averaged in time) becomes "calibrated" to the gaseous tracer concentrations.

For meteorological characteristics, three major measurement objectives are determination of the wind field (u, v, w) at various heights, determination of the vertical stability, and measurement of the atmospheric turbulence at various points upwind of the terrain obstacle. The wind field could be determined by a doppler acoustic sounder, or by a lidar device, or by tethersonde measurements. The acoustic sounder might have to be somewhat mobile to be locatable into the approximate upwind sector before the beginning of each day of experiments. Vertical stability could be obtained from the temperature profiles provided by an aircraft, tethersonde, or minisonde. In addition, a specially instrumented aircraft would provide detailed measurements of turbulence at various points.

All of these aircraft would also make measurements in Zone 3 approximately near the terrain, and possibly in Zone 4. The doppler acoustic sounder could continue to make measurements over the program study period in order to define the frequency of occurrence and duration of plume transport conditions believed favorable for terrain interaction.

- Interaction Zone (3). Zone 3 encompasses that area starting upwind of the hill where significant distortions of flow streamlines are thought to begin. It extends downwind from the obstacle an imprecise distance (perhaps at the downwind extent of the base of the hill or to a few height increments farther). Zone 3 then indistinctly blends into Zone 4.

The plume effluents transported through Zone 2 toward the terrain may experience a number of possible special phenomena. The end result of the joint action of these phenomena may be postulated to be anything, varying from no plume mass impaction upon the elevated terrain, complete impaction of the maximum possible value of plume concentration, or something in between these extremes. The problem is further complicated by the need to know the temporal behavior of what is little understood in the first place. The flow distortions effects within the interaction zone must be examined to parameterize their contributions to the variability of concentrations which may be observed at the terrain surface. These variabilities should be related to meteorological conditions. The resistance (or conductivity) of the slope boundary layer to mass fluxes of airborne (Zone 2) effluent to the slope surface must also be investigated; it probably is scale dependent.

Plume Characterizations. The transport and diffusion characteristics in the slope boundary layer may be critical to considerations (and understanding) of the plume impaction process. Requirements for plume measurements in this setting (all of Zone 3) include measurements of maximum tracer concentrations reaching within 1 or 2 meters of the terrain surface (sequential 60 min. average values at about 100 locations, plus sequential 10 min. averages at about 10 of these locations). Several (perhaps 5 to 10) short towers (on the order of 10 meters) could be placed at selected sampling positions to describe the change of tracer concentration with height. As an initial estimate of the spacing of samplers upon the elevated terrain, the following type of guideline is presented.

a) Horizontal spacing: determined from expected plume width parameter at the downwind end of Zone 2, e.g., about 0.5 to 0.8 σ_y.

b) Vertical spacing: determine from expected plume thickness parameter, in a manner corresponding to σ_y, about 0.5 to 0.8 σ_z.

c) Samples need not cover the entire hill. A band or capping array could be used, as appropriate to the controlled height of plume relative to the terrain.

Up- and downwind sides of the hill should be instrumented. Near-surface profiles of concentrations should be obtained from 2 or more tracer samplers located on the few short towers installed on the slopes. The cumulative sampling period for gaseous tracer should be consistent with the postulated six hour tracer release durations. Several 3 hour averages may be calculated from the six one hour sequential samplings within each individual 6 hour test.

Meteorological Characterizations. Meteorological measurements in Zone 3 are needed to define the wind field at several heights and positions about and above the hill. In a similar manner, temperatures should be measured to specify the thermal stability.

A tower should be located on top of the hill. Measurements of the gaseous tracer concentration profile and 3 or more levels of u, v, w, and temperature, plus turbulence parameters, should be collected during the experiments. Wind and temperature sensors (at 2 levels) should be placed and operated on several of the short (10 m) towers located upon the terrain slopes. The acquisition of turbulence data at these towers on the slopes could provide additional information of importance. If Gaussian formulations are unsuccessful, profile data might assist in the development of gradient or K-theory models of turbulent diffusive transfer within the slope boundary layers.

Some portion of the field site meteorological data should be available to be examined in near-real time (e.g., 2 minute averages updated every minute or two) to assist in quality assurance and guidance of the test preparations and conduct.

- Wake Zone (4). The zone downwind of the terrain obstacle tends to lie outside the primary area of interest. However, if several indirect and mobile sensing systems are utilized in the conduct of the experiment, or if atmospheric conditions change the behavior of the plume and local meteorological parameters, many potentially interesting and variable observations of opportunity could be easily collected. These data would either supplement on-going programmed measurements or substitute for those which would not be taken due to a departure from test window conditions. Measurements in this zone would be similar to the data collections in Zone 2. Airborne lidar observations of the particulate plume would be of significant value to show trajectories and wake diffusion downwind of the hill. Aircraft turbulence, wind, and temperature measurements could greatly increase the understanding of transport and diffusion in this zone (at least relative to the upwind Zones 1, 2, and 3).

3.2.4. Long Term On-Site Documentation. For the complex terrain situation, it is desirable to have an understanding of climatology of flows, stabilities, and perhaps other parameters that control whether an elevated plume will cause high ground-level concentration on a hillside. It is necessary to determine, for various time averaging periods, the frequency at which concentrations occur within twenty-four hour periods and [illegible] periods extending out to the entire year (second-highest concept).

It is also important that we know what other kind of terrain induced flow and turbulence phenomena might be occurring in the area, but which were not observed during the study period.

Therefore, it is important to continue some of the more routine measurements at the study site for some additional time, perhaps a year, before and/or after the conclusion of the intensive field experiment(s). The most important parameters to continue measuring may be winds, as a function of height, and the vertical stability. An acoustic sounder system(s) might fulfill these needs for wind and vertical extent of turbulent mixing or its layered structure.

3.2.5 Additional Experimental Considerations. Prior to final experimental design and the physical setup of a field measurement site (and perhaps before final selection of that site) several screening studies could be performed. These screening studies should suggest appropriate sampling resolution (temporal and spatial) and some of the more important physical phenomena to be quantitatively measured. The following examples of screening studies may be valuable before development of the final field study design. Monitoring data from sites surrounding sources of opportunity should be screened. If the temporal resolution of the plume(s) of opportunity is on the order of minutes to an hour or two, meaningful guidance may be gained regarding peak to average effluent concentrations with some implications for controlled tracer sampling equipment.

Turbulence measurements previously collected within complex terrain settings should be reviewed for insight about expected phenomena and their aproximate quantitative values. Recently, turbulence measurements have been collected by researchers to describe the airflow environment for wind energy systems which might be located on the top of ridges and hills. These data should be studied.

A number of preliminary visual tracer studies should be conducted on and around the candidate field study sites. Some knowledge of the size and strength of terrain slope boundary layers and airflows may be gained. In this way, the bias due to selection of a particular size of terrain feature (scale related subordination of some phenomena) may be quantitatively revealed.

Finally, physical modeling of the selected site may provide valuable insight for the final experimental layout of measurement devices. Focal points for measurements (characteristic spatial locations on and about the hill) may also be suggested.

Another approach to the conduct of this plume impaction study is the separation of the investigations into two component parts, each of which is conducted somewhat separately. (To some extent, the small hill (50 to 100 m) study may be an evaluation of impaction behaviors without the likelihood of significant influences from slope boundary layers and flows). The phenomena which govern the impaction process may be separated into phenomena which occur either near the terrain (within the slope boundary layer and flows) or not near the elevated terrain. Investigation of plume mass transfers through the slope boundary layer would be expected to be site and site-scale specific; measurements for several different settings would be required with detailed, fine-resolution measurements. These measurements would describe the micrometeorological behaviors within the slope boundary layer; the plume mass fluxes through this layer would be analogous to a plume deposition study (usually conducted above flat, simple surfaces). The second component of investigation would study the transport and diffusion of airborne effluent to the point of either impacting upon the terrain (if no significant boundary layer exists) or to the point of increasing influence of the slope boundary layer processes. This second component of the study relates to the site climatology of transport and diffusion in the general vicinity of the topography; it describes the concentration of plume effluent, the frequency of its occurrence, and its spatial location. It is analogous to a potential for impaction; the near-slope component describes the receptivity of the slope boundary layer to a mass flux through it to the terrain surface receptors. Both components of the study must be addressed; this alternate consideration simply poses the idea that the overall study might be decomposed into smaller research modules with fewer specific focal points within each module. With more but smaller and specific research modules, the time period for development of an overall description (model) of plume behavior could be lengthened unless several modules may be run concurrently with each other.

3.3 Summary and Conclusions

The understanding of impaction of plumes from tall sources against topographical features is the primary goal of this experimental design. Thermally stable atmospheric conditions are the focal point, but neutral and transitional conditions should also be understood. In the first stage of experimentation, a hill of simple geometry and relatively isolated from other elevated terrain is suggested; it should have a size commensurate with real sites about power plants in the western United States. The essence of the study is a combination of meteorological and gaseous tracer measurements which must satisfy the following minimum requirements (at least as viewed by this panel) during a particular field test.

A set of tracer data points must be collected which clearly describes the magnitude and rate of dilution of the airborne effluent as it approaches the elevated terrain. A projected (expected) concentration value must be obtained, for the position of plume impaction upon the terrain slope, were no alterations of airflow and rate of diffusion to occur before plume impaction. The observed concentration versus the projected concentration demonstrates the degree of impaction. A null concentration observation indicates no impaction. More subtle features, such as the concentration gradient in the boundary layer immediately adjoining the slope, is an interesting facet of the problem and should clarify the role of the micrometeorology within the layer relative to the impaction problem.

Sufficient measurements of the meteorology, transport (visualizations both of the plume and slope flows), and turbulence should be collected to document the dynamics of the problem. Routine site monitoring measurements should cover a longer period than the intensive field studies; these data may help resolve the uncertainty about what magnitudes of plume concentration impact for longer period averages.

Finally, pre-field test physical modeling simulations may guide a final design of the field installation. Also plume visualization should be used more frequently than just during full scale experiments. Many specific phenomena may be qualitatively investigated (and photographed) by smoke flows around the obstacle, and by small scale releases within the slope boundary layer flows.

3.4 Budget Estimate

In order to estimate the general feasibility of the cost of the field experimental design, the following approximate values are provided. A study about a 400 to 600 m high hill is postulated. Two 40 day intensive field study periods are assumed, with 50 days of field sampling and measurement operations. Continuous meteorological data collection and archiving for an 18 month period are assumed. The costs of centralized data logging equipment are omitted from this estimate and should be included elsewhere.

3.4.1	Equipment and Other Direct Costs	$ 2,147.600.
3.4.2	Labor 135 man months @ $30/hr (22 days per month)	712,800.
	TOTAL (Labor, Equipment, and Other Direct Costs)	$ 2,860,400.

4. MEASUREMENT TECHNIQUES PANEL

PANEL LEADER: Roy Evans

PARTICIPANTS:

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1. SCALE OF MEASUREMENT

Measurement techniques appropriate for three scales of experimental design were discussed by the Measurement Techniques Panel. The smallest scale considered was appropriate to controlled tracer releases over a small hill, with plume travel distances of km, as described in the scenario submitted by Bill Snyder. The next larger scale discussed was appropriate to the concept of controlled release over a 500-meter hill, with plume travel distances of about 10 kilometers, as described in a scenario proposed by the Experimental Design Panel. The largest scale proposed was appropriate to impingement of plumes on elevated terrain (hills) near an active power plant.

The chief differences among these three scales are related to measurement resolution and plume sizes. The small "100-Meter Hill Experiment" would involve relatively thin plumes with initial vertical sigmas between 5 meters and 15 meters. The "500-Meter Hill Experiment" would involve plumes with vertical sigmas of 40 to 60 meters prior to impact on the hill. The full-scale experiment would also involve plumes with initial vertical sigmas on the order of 40-60 meters; however, these would evolve over longer travel distances (10 kilometers or more) to widths of more than 2 kilometers.

Investigation on the impingement of a plume on a hill under stable conditions, regardless of the scale of the experiment, was considered to have four phases:

(1) PLUME RELEASE AND GENERATION (i.e., determining the plume's source terms and initial conditions);

(2) PLUME EVALUATION (i.e., the growth and changes which affect plume dimensions during plume transport);

(3) PLUME IMPINGEMENT (the actual process of transport of pollutant material through the boundary layer); and

(4) FLOW FIELD DETERMINATION (measurement of wind speeds, wind directions, turbulence, thermal structure and stability, of the wind field which actually transports the plume.

Each of the three scales of experimental design involves measurements of these different aspects of plume generation, transport and evolution, and impingement on elevated terrain. However, each scale involves plume dimensions and resolution requirements which determine the choice of measurement techniques. Table 1 is a summary of techniques and their probable applicabilities to the experimental scales.

Discussion of these techniques is organized generally in terms of experimental scale, beginning with the small-scale experiment and going on to the full-scale (or Real-World) experiment. An experimental technique is discussed under the first experimental scale where it becomes useful.

2. MEASUREMENT TECHNIQUES FOR SMALL SCALE EXPERIMENTS

This scale of effort, as discussed by the Measurement Techniques Panel, is similar to the concepts described in the Snyder Senario for the 100-meter hill experiment. Broadly speaking, modern technologies (lidar - instrumented aircraft, remote windfinding systems) are not appropriate to experiments at this scale, and researchers must rely primarily on conventional techniques: instrumented towers for winds and temperatures, integrated samples (by syringe or bag) for a gaseous tracer (probably SF_6), and plume visualization by smoke release.

The panel did make some specific suggestions for the conduct of the 100-meter hill experiment, which can be summarized as follows:

(1) Little cost would be added to the experiment by release of two different tracer species (e.g., SF_6 and Freon-13) from two

TABLE 1. SUMMARY OF MEASUREMENT TECHNIQUES AND THEIR PROBABLE APPLICABILITIES TO EXPERIMENTAL SCALES.

	Small Hill (100 m)	Medium Hill (500 m)	Full-Scale or "Real World"
Plume Generation and Release - initial conditions	Controlled release; SF_6 or freons, hydrocarbons for concentration -- 2 points? Smoke Tracer	Controlled release (Same as small hill)	Power plant or other stack with monitor for SO_2, NO_x - flow measurement temperature-tracers and COSPEC?
Plume Evolution (Cross-sections, height, location)	Plume visualization and photography; illumination; tower instruments; ground-based electric field sensors	Ground-based lidar and airborne lidar; in situ aircraft sampling; ground-based and airborne electric field sensors	Ground-based lidar or aircraft (in situ)
Plume Impingement (Surface concentrations, tracers SO_2, SF_6, PBL)	Tracer measurements Flow visualization (photo)	Tower measurements (photo) of oil smoke Tracer measurements Airborne lidar or ground-base lidar	Tower — Tracer SO_2 or pollutant; — Airborne Lidar
Flow Field (Wind speed, direction, turbulence, mixing depth, humidity, temperature)	Towers (need high frequencies) Acoustic Doppler FM/CW radar or lidar; tethersondes	(Routine) Towers Accoustic Doppler FM/CW or lidar (Intensive) Tetroons	Minisondes Towers Accoustic Doppler Tetroons FM/CW Aircraft

different points, and dual release would enhance chances of observing a plume within the sampling network and would very likely improve knowledge of the wind flow field.

(2) The problem of sampling the plume prior to impact on the instrumented hill is, at best, difficult. Concentration measurements can be achieved only by instruments on towers, which are expensive to install and operate, and which cannot be established with sufficient density to describe the plume prior to impingement. The use of a ground-based lidar for this purpose is not recommended by the panel for two reasons: (a) the normal minimum resolution "cells" for existing instruments are on the order of 3 meters, and reducing this to 1.5 meters to resolve the small plume as was suggested in one of the plenary sessions is pushing the instruments into operational areas where their performance has not been verified. Even if the instruments can, in fact, achieve practical resolutions of this order, a relatively small number of cells would be obtained within a plume cross-section, and the feasibility of performing accurate contour mapping of the plume cross-section cannot be assumed a priori. The feasibility of any such application should be verified before including it in the small-scale experiment. (b) The ground-based instruments are expensive to operate ($40,000 to $50,000 per month in the field), and other methods would be more cost effective. A more effective method suggested by the panel is the "Laser Illuminator" concept, discussed below.

2.1 Gaseous Tracers

The proposed experiments to study plume impingement on hills or ridges require the use of a non-reactive, non-depositing tracer that can be released at precisely controlled rates and measured accurately at low concentrations. For the distance scales being considered (i.e., a few hundred meters for a "small hill" study to a few tens of kilometers for a full-scale study at an existing plant site), sulfur hexafluoride (SF_6) appears to be the most suitable tracer. It has been used extensively as a meteorological tracer and reliable methods of release, sampling, and analysis are available. Background concentrations in the atmosphere average about 0.5 parts per trillion (ppt) and commercially available electron-capture gas chromatographs can measure SF_6 concentrations accurately down to 1 or 2 ppt. This sensitivity is quite adequate for tracer measurements out to about 100 km from the release point. This tracer is readily available at a cost of about $3 per lb.

Other gaseous tracers currently under development, for example, perfluorocarbons and heavy methanes, with far greater measurement sensitivity (.01 ppt or less), are intended primarily for use to distances well beyond 100 km. If multiple tracers are desired, fluorocarbon 12B2 (CF_2Br_2), 114B2 ($C_2F_4Br_2$), fluorocarbon 13B1 (CF_3Br) are available at somewhat higher costs than SF_6.

A potential problem in the use of SF_6 in meteorological experiments is the variability of the background concentrations. It is used in large quantities as an insulating gas in high-voltage power transformers and switches, hence, there are a large number of sources that may produce localized concentrations well above the average background level. A survey of local SF_6 concentrations should be included in the site selection process.

2.1.1 Tracer Release. SF_6 is supplied as a liquified gas in pressurized cyclinders and can be released by a gas directly from these cylinders.

Required release amounts would be on the order of 1 lb/hr for the proposed "small hill" experiment; about 10 lbs/hr for the "large hill" experiment (distance scale of about 10 km) and about 100 lbs/hr for the plant site study (scale of about 50 km). Individual release durations of 3-6 hours should be sufficient to accomplish the objectives of this study. Elevated releases can be managed with no great difficulty.

Since one objective is to study the effect of release height in relation to hill height and stabililty profile, it would be more efficient to use two or even three different tracers (i.e., SF_6, 12B2, and 114B2) released simultaneously at different altitudes, at least for some tracer trials. Releasing tracers from different locations might also maximize the information gained from each trial.

2.1.2 Tracer Measurements in Plume Evolution. It is desirable to measure tracer plume concentrations and horizontal and vertical dimensions during its travel from the release point to the terrain feature of particular interest.

Real-time continuous SF_6 monitors are available which can be flown in a small aircraft to provide profiles of SF_6 concentrations during a plume traverse.

One version of this instrument, developed at Brookhaven National Laboratory (BNL), uses the frontal chromatography technique to provide continuous (but time-delayed) in-flight data for a period of 90 seconds or more. It must then be backflushed for about 2 minutes in preparation for the next 90-sec plume traverse. This instrument has been successfully flown on many occasions.

Under contract to the NOAA Air Resources Laboratory, Lovelock has developed a truly continuous real-time instrument by eliminating the need for a chromatograph column. This instrument can be used either with SF_6 or perfluorocarbons and is still under development by Lovelock as well as by Dietz at BNL. Lovelock expects to deliver a flight-worthy prototype by January 1980. Its sensitivity should extend well below the parts per trillion level, with a response time on the order of 1 second.

Unfortunately, none of these instruments will have sufficient resolution to obtain a true profile of the very narrow plume expected in the "small hill" experiment. They will, however, be able to detect the plume and provide crosswind integrated concentrations through the plume. The real-time instruments will be able to provide a great deal of data on tracer concentration profiles as a function of altitude and distance from the source for the larger scale experiments.

2.1.3 Plume Impingement. All three scenarios being considered will require an extensive array of about 100 samplers to measure tracer concentrations in the vicinity of plume impingement on the major terrain feature.

Several methods are available for collecting whole-air samples for SF_6 analysis. The NOAA Air Resources Laboratories Field Research Office (ARLFRO) at Idaho Falls has developed a battery-powered sampler that pumps air into a plastic bag, providing a time-integrated sample at $100-200 per unit. The units must be switched on and off manually. Several hundreds of these samplers are on hand at ARLFRO. Automated sequential whole-air samplers, using bags or syringes, are commercially available at a cost on the order of $2,000. An automated sequential sampler, developed at BNL, collects up to three samples in evacuated steel cylinders. The system is radio-controlled for simultaneous operation of all samplers. Twenty samplers are available at present.

Considering the large number of samplers required (100) and the relatively short sampling intervals desired (10 min to 1/2 hr), a commercial automated sampler, providing 24 syringe samples, would appear to be the best choice. The other types of samplers can be used to augment this network.

For the "small hill" experiment in particular, the sheer number of samples required may be overwhelming (100 samplers x 6 samples/hr x 4 hours = 2400 samples per trial). Meteorological data or smoke plume information will have to be used for screening, to select perhaps 10% of the samples for immediate analysis in preparation for the next trial.

An alternative, to provide quicker turnaround, would be to use analyzers that provide real-time readout (at 2-5 minute intervals of concentration) to be fed into a centralized computer. The cost of such analyzers (about $6,000 each) plus the computer hardware would have to be weighed against the cost of manual processing (perhaps $1/sample) and the need for rapid data processing.

2.2 In Situ Measurements of Wind, Temperature, and Humidity from Towers and Balloons

The measurement of meteorological variables -- wind, temperature, humidity, pressure -- by in situ instruments in shelters or on towers provides the data core for most field experiments. This will be true for the proposed complex-terrain plume tests also. A brief review of the expected accuracies and applicability of such measurements is, therefore, in order.

For measurements of mean wind quantities, propeller or cup anemometers with vanes as required, are quite suitable if the instruments are properly exposed away from flow obstructions.

Standard cup and vane systems have a general accuracy of +5° in direction and about +0.2 m/s for wind speed. Resolution of the wind direction is obtained to one degree. Wind speed threshold is in the neighborhood of 0.25 m/s, but reasonable vane response to wind gusts is limited to speeds above 1-2 m/s.

Temperatures on the tower are generally recorded with a thermistor or a platinum resistance thermometer in an aspirated radiation shield. Absolute accuracy of the thermistor is about 0.5°C with resolution to 0.1°C; somewhat better accuracy and resolution are available with the platinum resistor. Temperature differences on the tower are recorded by voltage balancing between the two sensors. Accuracy of Delta-T with thermistor is about 0.1°C.

Relative humidity is best measured on the tower by a dew-point hygrometer system. Accuracy is in the neighborhood of 0.5°C.

For the accurate eddy-correlation measurement of turbulent plumes, the distance constant for anemometers and the response time for temperature sensors must be short enough to resolve all eddies of significant size. If we are to really understand the turbulent impact of plumes onto rough terrain through the atmospheric surface layer, then instruments with at least a ten hertz bandwidth must be used. This implies hot-wire or sonic anemometers and fine-wire resistence thermometers. Since three-axis sonic anemometers-thermometers have demonstrated their accuracy (to small fractions of a degree and a meter per second) at the NOAA/NCAR Boulder Atmospheric Observatory, they are a logical choice for turbulent surface layer measurements. Data processing algorithms compatible with mini-computers are also available.

2.3. Meteorological Towers

In situ instruments must be appropriately mounted, frequently on towers, to place the instruments at the desired heights. Tower costs increase quickly with increasing height. Estimates for costs of installed towers, with no instruments, were obtained by asking for bids from a California-based contractor subsequent to the end of the Workshop. These estimates assume that the towers will be stressed for ice, wind, and lightning, and that they have de-icing heaters. Each tower is equipped with four instrument elevators, with a 19-wire cable to each elevator. Cost estimates were as follows:

HEIGHT	COST
50 meter	$30k
100 meter	$41k
150 meter	$75k

2.3.1 Remote Wind Sensing in the 100-Meter Hill Experiment.

The excellent range resolution and short-range measurement capabilities of FM/CW radar provide important advantages for monitoring the the small-scale experiment. Should there be fine scale wind shear, as frequently occurs in stably-stratified valley atmospheres, this system will be able to measure it. Further, the intensity of the return delineates these shear zones, thus providing a record of descending temperature inversions and the ubiquitous gravity and shear waves associated with such interfaces. Real-time wind readout will also aid in properly placing the plume sources.

With the range of the radar of several kilometers, changes in the mesoscale or synoptic scale wind structure that might influence the experiment can also be monitored. Thus, the arrival of warm fronts, or density currents riding over and eroding the surface-based nocturnal inversion, can be anticipated.

Supplementing the radar with CW Doppler lidar or Doppler acoustic sounders is also attractive. These lower cost, more mobile sensors can significantly expand the volume of the atmosphere being measured for winds.

2.3.2 Wind Measurements with the FM/CW Doppler Radar. The FM/CW radar detects radiation backscattered from index of refraction turbulence structure in the clear atmosphere. A 10-cm wavelength unit developed at the NOAA Wave Propagation Laboratory employs phase measurement to detect the Doppler frequency shift from the moving turbulence that advects with the wind. Good signal-to-noise ratio is obtained at ranges up to several kilometers, and the minimum range can be as short as 20 or 30 meters. Range resolution as small as 1.5 m is feasible, and radial velocity accuracy of 0.1 m/s has been demonstrated. Ground clutter restricts elevation angles to 20° or greater.

To measure both components of the wind, u and v, the radar performs a conical scan about the zenith in a so-called VAD (velocity-azimuth display) mode. Asymmetry of the VAD velocity about zero provides a measure of the vertical velocity, averaged over the diameter of the scanned circle. A minicomputer in the system provides real-time readout of winds versus height. Separate transmitting and receiving antennas are mounted on a trailer, and a separate semi-trailer houses the radar electronics and data processor. Setup time for the equipment is approximately one day on a level site 20 m x 40 m; three-phase 208V or single-phase 240v, 10 kw is required. A two-man per shift crew can operate the radar once it is in place.

2.3.3 Wind Measurements with CW Doppler Lidar. A number of CW Doppler lidars have been developed (at NOAA, EPA, DOT/TSC, NASA, Marshall) to measure winds by monitoring the frequency shift in 10.6 m radiation backscattered from atmospheric aerosols. These CW units obtain range information by focusing the infrared radiation at the desired range, where the backscattered radiation then mixes efficiently with the laser local oscillator on the photodetector. These systems are quite suitable for VAD wind measurements in the clear air at ranges to 500 m, although range resolution is quite coarse at ranges beyond 100 m because of the elongated focus for typical optical apertures of 20 to 30 cm. The units are all mounted in self-contained trucks. Setup time on a level site 10 m x 15 m is four hours. Single phase 220V power, 5 kw, is required. A two-man crew per shift is required.

2.4 Laser Illuminator

- Experimental Use. Plume visualization for the proposed small hill experiment can be accomplished using an aerosol tracer and several laser illuminators with suitable recording devices. The measurement technique is only applicable to a nighttime release. Several laser illuminators are positioned between the source and the hill, establishing thin planes of light perpendicular to the plume path (see Figure 8).

Plume location is readily observable by the experimenters and plume dimensions can be established through conventional photographs or video taping with one or more cameras positioned along the axis connecting the source tower and the hill.

- Equipment Description. All components, are readily available. Cost of the laser illuminator and camera for each plane is estimated to be $10,000, with accuracy not limited by the experimental configuration but by the effort expended on edge detection in the images. Illuminators could be strobed to establish timing. Another approach using search lights may be possible.

2.5 Detection of Small Plumes by Electric Field Measurement

Electric field measurements in connection with plume trajectory studies are a novelty and need further exploration. However, if the artificial smoke particles are charged electrically, so as to perturb the atmospheric electric field measurably, field measurements can be a powerful tool to detect a plume or even measure the concentration of particles in a plume. This could be done remotely from the ground by measuring the field as function of distance from the centerline underneath the plume with a field mill mounted on a movable platform like a car. This could also be done airborne by a mill mounted in the nose of a model airplane that is remotely directed across and through the plume. The model aircraft speed is slow enough to achieve spatial resolution of 10^{-2} meters. The technique, therefore, would be applicable to scales that are expected in the 100- and 500-m hill studies.

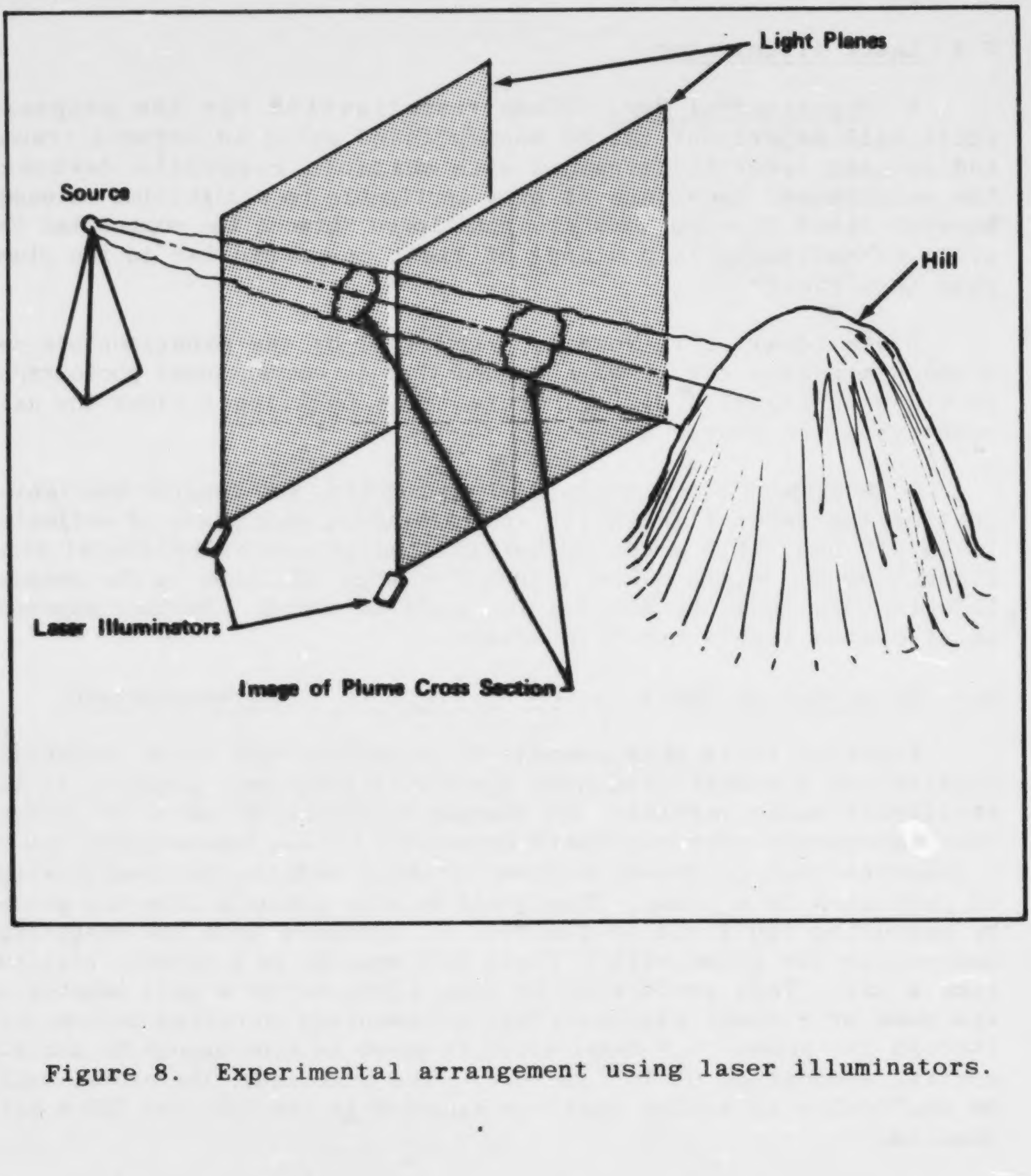
Light Planes
Source
Hill
Laser Illuminators
Image of Plume Cross Section

Figure 8. Experimental arrangement using laser illuminators.

3. MEDIUM-SCALE OR 500-METER HILL EXPERIMENT

In this experimental scale, initial vertical sigmas are on the order of 40 to 60 meters, with travel distances of the order of 10 kilometers, and plume elevations of 250 to 750 meters. At these scales, the conventional tower-based wind measurements must be augmented or supplemented by tethersondes, minisondes and remote devices. The doppler acoustic sounder is particularly well-suited to operations on this scale, as is the FM/CW radar. Tetroons may be useful for defining trajectories.

Plume dimensions are large enough to satisfactorily use ground-based lidar units for dispersion parameter measurements; airborne lidar can contribute to mapping the impingement of the plume on the hill, provided the plume is tagged with a conservative particulate tracer and is large enough. In situ sampling with instrumented aircraft may or may not be useful, depending on the plume dimensions selected for the release. To effectively use aircraft, plume dimensions must be of the order of several hundred meters to a few kilometers; plumes less than a hundred meters are too narrow to effectively measure with aircraft. Turbulence and wind fields aloft, however, can be effectively measured with instrumented aircraft.

3.1 Flow Field Determination by Doppler Acoustic Sounding

Transmission of an acoustic pulse upward, and measurement of the doppler shift of the echo which is returned from small scale atmospheric turbulence, are the basis for one technique for the remote measurement of winds aloft. Such instruments, which are now commercially available (at a typical cost of $40 to $50,000) can be used in a complex terrain study to define the wind and turbulence fields aloft, to determine the depth of the mixed layer, and to illuminate localized phenomena such as shear layers, inversion layers, and thermal plume activity. Recently-developed instruments can be mobile and have a useful range around one kilometer, which makes them effective for intensive or routine field studies of plume dispersion aloft.

Two different configurations of the Doppler acoustic sounder are available. Bistatic configurations, based on designs developed at the NOAA Wave Propagation Laboratory (WPL), are manufactured by the Radian Corporation. A bistatic unit with a somewhat different configuration has been manufactured by Xonics, Inc. The NOAA WPL also has several bistatic units of its own design. (Such instruments have a maximum range of 600 to 800 meters and a minimum range of from 100 to 200 meters above the ground). Monostatic configurations, based on a design developed at the University of Melbourne (Australia) are manufactured by AeroVironment, Inc. These instruments have a demonstrated maximum range, under appropriate meteorological conditions, in excess of one kilometer, and a minimum range of under 30 meters. All of these instruments have different signal processing techniques for extraction of the wind speed; some of the performance specification differences cited here depend both on the configuration and the processing scheme.

Either type of instrument has a wind speed resolution of about 0.2 m/s and a maximum wind speed measurement capability of 25-35 m/s. Vertical resolution of wind speed data is typically 30 m, although resolution down to 10 m is attainable.

These resolution scales make acoustic sounders best suited for studies around larger terrain features, although they can provide useful data on the higher level winds over smaller (100 meter) hills. The absolute accuracy of these instruments is not well known. Tests of acoustic sounders next to the NOAA WPL 300 m tower in August 1979 should provide some information on this question.

The choice of bistatic versus monostatic configuration depends on a number of factors. Bistatic units require a substantial area (several hundred meters on a side) for laying out three or four antennas; the monostatic antennas are all located at one point, and mobile units are available.

The bistatic system measures the wind in a single vertical column of the atmosphere; monostatic units make measurements in several directions from the antennas, and then require an assumption of wind field homogeneity to construct all wind components. In either case, the wind measurement reflects an average value over a substantial volume of air.

The lower height limit of bistatic systems is substantial, and depends on the lowest altitude at which the transmitting and receiving antenna beams cross; monostatic system measurements, on the other hand, can begin very close to the surface.

The maximum range of bistatic systems is also defined by the antenna geometry, while signal-to-noise considerations define the upper limit of monostatic configurations.

Because of the siting considerations, monostatic doppler acoustic sounders are probably best suited for the proposed complex terrain study. Their versatility probably outweighs the disadvantages of this configuration.

The routine recording of turbulence aloft by doppler acoustic sounding should be possible by 1980. With the support of the Electric Power Research Institute, AeroVironment is currently evaluating various algorithms for the derivation of diffusing turbulence levels from doppler acoustic signals. This evaluation includes testing of these algorithms against in situ turbulence measurements made on an instrumented tower. The resolution of such data should also be on the order of 0.2 m/s (or better) for the root-mean-square wind speed variation. This resolution will be adequate for defining diffusion under all but the most stable conditions.

Derivation of the mixing height from the turbulence field is straightforward. In addition, display of the amplitude of the return signal in the traditional time-height form of a non-Doppler acoustic sounder record, can illuminate the atmospheric structures (shears, thermal plume, inversions, local fronts) influencing the transport and dispersion of the plume.

3.2 Flow Field Determination by Tethersonde

For measurements of the structure of the planetary boundary layer, a sensor package carried aloft under a tethered kytoon was developed several years ago at the National Center for Atmospheric Research. This instrument is now commercially available from Ambient Analysis, Inc., in Boulder, Colorado, under the trademark of Tethersonde, for $8,000.00 to $10,000.00, depending on the options selected.

The Tethersonde instrument package consists of sensors for wind speed, temperature, pressure, wet bulb temperature, and the orientation of the package relative to magnetic north (which serves as an indicator of wind direction since the instrument package orientation follows that of the kytoon as it points into the wind). An optional thermal structure function, C_T^2 sensor is also available. A rechargeable battery provides enough power for about four hours of continuous operation.

The package is carried aloft by a small, 3.25 m^3 kytoon. With relatively light winds aloft (less than 10 m/s) the Tethersonde can reach an altitude of 1 km above the surface at a cool, sea level site. To provide additional lift for use in stronger winds or at higher altitude launch sites, a 4.25 m^3 kytoon is also available. A motorized winch handles the tether line.

A radio-telemetry system cycles through all data channels once each 30 seconds and transmits the signals to a ground based receiver. The data is printed on paper tape, along with the time of each scan. An optional programmable calculator can be attached to the system to calculate the balloon altitude by integrating the barostatic equation, using data obtained during the ascent, and can also record all data on a tape cassette for subsequent computerized analysis.

The Tethersonde is a versatile sounding tool for exploring the structrue of the planetary boundary layer in all scales of complex terrain. It is particularly useful for study of the flow over and around a hill. Since it can be tethered at a relatively constant height, it can be "parked" at the altitude of a plume and will then provide a continuous record of the direction and speed of the plume-transporting wind.

The system is portable, and can easily be operated by one person with some practice, as long as surface winds are not strong. The ground station requires 110V, 60 HZ electricity, which can be provided by an inverter and a car battery. Launching and retrieval in strong surface winds (above 10 m/s) is difficult, as is operation when winds aloft exceed about 20 m/s.

The response ranges and precision for the various components recorded by the tethersonde are:

Wind Speed	0.5 - 20 m/s	±0.25 m/s
Wind Direction	0 - 360°	±5°
Temperature	-50 - +50°C	±0.5°C
Pressure (Difference Relative to Surface)	0 - 100 mb	±1 mb

3.3 Minisonde

Simple, expendable instrument packages, similar in concept to the Tethersonde package, can be carried aloft by pilot balloons to provide soundings of temperature to heights greater than those attainable by the Tethersonde. Tracking of the minisonde balloon by theodolite allows calculation of the wind speed and direction profiles, provided that the ascent rate of the balloon is known. In flat terrain and a slightly stable atmosphere, the ascent rate can be assumed to be constant. In complex terrain, or in unstable or strongly stable atmospheres, a pressure sensor on some makes of sondes provides a direct record of the balloon height or a second theodolite is needed to determine the balloon height. Some sondes also record wet bulb temperature.

The minisondes are similar in concept to radiosondes, but are easier to handle and much cheaper. Although automatic radio tracking of the sondes is not possible, the ground stations for minisondes often provide for digital data recording on cassettes, and can contain all of the features of the automated Tethersonde ground station. Minisonde sensor performance specifications are generally almost comparable to those of the Tethersonde: The wind data derived from theodolite tracking is less precise, however, and its quality depends continually on operator skill.

Minisondes are useful for all scales of complex terrain studies. Because of the discrete nature of the soundings, and their cost, the sondes are best used to study slowly varying phenomena, such as flows well above the surface.

3.4 FM/CW Wind Finding

All that has been said about the FM/CW radar for wind measurements in the smaller scale experiment applies here as well. The range of the radar to several kilometers is even more important here, where towers cannot reach into the plume heights.

3.5 Flow Field Determination by Aircraft

Within the framework of the "medium hill" experiment, the light aircraft can extend the meteorological observation of the plume environment. This can be best accomplished through horizontal traverses perpendicular to the plume trajectory. Sampling flights through the plume can be used for this purpose, although it may be desirable to extend the horizontal traverses somewhat. Principal objective of the measurements would be to determine the homogeneity of the wind and turbulence environment at plume level.

Parameters of concern are:

1. Three-dimensional velocity components (u,v,w) sampled at 100 HZ so that turbulent components as well as average values can be determined. Turbulence parameters are measured by a gust boom referenced to gyro-accelerator system which provides a measurement platform stable to low frequency fluctuations.

Turbulence data can be processed into σ_θ and σ_ϕ values for a range of averaging time. Thirty second averaging (about 1 km of flight path) is probably the longest time acceptable for horizontal mapping. Accuracy is reported to be + 0.1 m/s (Gilmer, McGavin and Reinking, 1978). Through these measurements, a horizontal map of wind and turbulence can be obtained at plume level to be used in modeling inputs.

2. Flux parameters can also be measured if desired during the horizontal traverses. Both vertical height and moisture fluxes can be obtained by cross correlation of temperature and humidity fluctuations with vertical velocity variations. These data form an independent measure of the diffusion environment.

3.6 Tracer Measurements Via In Situ Instrumented Aircraft

The space resolution of aircraft measurements depends critically on aircraft speed and response-times of the instruments. Light-twin aircraft can be flown at speeds of 50 m sec^{-1}. Time constants of instruments and gas measurements must be of the order of one second. Hence, the space resolution of the sensing equipment is of the order of 50 m. This is probably good enough for tracer experiments of the scales in question for this experiment.

Instrumented aircraft can be used to measure in situ the concentration perpendicular to the axis of the plume of tracer gases (SF_6) and particles (total concentration, flight scatter coefficient).

It is proposed to measure centerline concentration and horizontal dispersion of particles and gases. Repeated measurements result in a mean centerline concentration and horizontal dispersion (σ_y) of plume effluents. Repeating the measurements at different heights from the axis gives the vertical dispersion (σ_z).

Performing the measurements at different distances from the source upwind and downwind of the obstacle (hill) results in the downwind dispersion at both sides of the hill, indicating the effect of the hill on plume movement. Aircraft tracer measurements, including data processing, will cost about $8,000/day, for most contractors.

3.7 Lidar

- Equipment Description - Several ground-based, van-mounted lidar systems are available which are suitable for this type of experiment. Systems are available with calibrated scanning mounts, a feature necessary for obtaining detailed plume cross-sections.

Spatial resolution of current systems approaches several meters, adequate for all experimental scenarios considered. All lidar systems have real-time display capabilities and thus can be used to locate plumes or to direct other experimental efforts into plumes. Data output is in the form of hard copy line profiles, density plots, density contour plots, and processed and unprocessed magnetic tapes.

3.8 Ground Based Lidar

- Experimental Use - The ground-based lidar would find utility in both the middle-sized hill experiment, and in a full-scale experiment involving an actual power plant source. Much field work of this nature has been routinely performed for a number of years, and the methodology and equipment are well proven. The spatial resolution of existing devices is comparable to the dimensions of the small-scale experiment, but other methods of determining plume location or dimensions may be more cost effective at this scale (see LASER Illuminator). The ground-based lidar can be used primarily to determine plume dimensions and, in particular, the behavior of the plume as a function of time. A workable method of determining source content is plume sampling by aircraft, with subsequent extrapolation and averaging of plume concentrations using lidar information taken over extended time periods. The lidar can also be used to determine plume impact points with proper safeguards for eye safety of experimental help.

Some features of specific systems might have additional benefit to the experiment depending on the actual site chosen. For example, one available system (NOAA) has the capability of measuring depolarization ratios and thus discriminates between spherical particles (i.e., combustion particles, oil droplets, etc.) and background fugitive dust. Another system (SRI) can be used in a mobile mode pointing vertically upward. If extensive road networks exist and the scale of the experiment is large, this might prove of benefit over scanning systems. The lidar systems could also be used to obtain meteorological information when not being used to for plume measuremeasurements.

- Costs - Ground-based lidar systems can be operated for around $50K/month excluding travel cost.

3.9 Airborne Lidar

The airborne lidar maps aerosol distribution beneath the aircraft. In particular, the airborne lidar can be used to find the dimensions and location of plumes. In the context of the three scenarios considered, the airborne lidar would only have utility in the medium hill controlled release and the monitoring of the effluent from an actual power plant. The airborne lidar and the ground-based lidar can be used to determine plume location, cross-sections between the source and the plume, and in addition, the airborne system can be used to position a sampling aircraft within the plume for source term determination. Flights over the subject hill in either the controlled release middle size hill, or full-scale hill experiments, would yield plume impact information. Figure 9 shows airborne lidar returns several kilometers downwind from a power plant source. The second trace from the left side of the photo shows little scattering at ground level, whereas, the third trace shows considerable scattering due to plume impact.

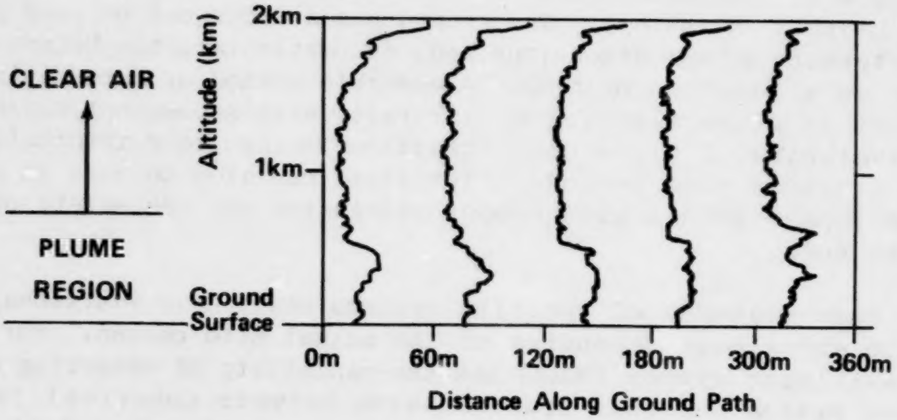

Figure 9. Downlooking airborne lidar showing plume contact with ground. Note ground level scattering on center trace.

3.10 System Description

- System Description - At the present time two operational airborne lidar systems exist and are operated by the EPA Research laboratory in Las Vegas (EMSL-LV). The system of interest is the latest device developed by that laboratory; a two-frequency Lidar utilizing a Nd-YAG Laser with a doubling crystal. The device has a vertical resolution of 10 m and horizontal resolution dependent on aircraft ground speed and the highest frequency of operation (10 Herz). The system's weight and power requirements are compatible with small twin-engined aircraft. In this type of platform the horizontal resolution is approximately 6-10 meters. The device has real-time display capabilities on board the aircraft, thus enabling the operator to tell other personnel the plume location and height and to position other sampling aircraft into the plume. A ground-based computer system is used to display and to provide hard-copy output in short time turnaround after the aircraft lands.

Another airborne lidar system is currently under development by SRI.

- Systems Cost - A rough estimate of total system costs including aircraft and ground-based data system is $4,000.00 per day of operation.

4. MEASUREMENT TECHNIQUES FOR FULL-SCALE TRACER AND ACTIVE POWER PLANT STUDIES

All of the instrumentation mentioned so far can be used with full-scale tracer studies and studies of the active power plant; however, the scales of measurement are now large enough that remote and aircraft measurements become most economical for most parameters. The panel recommended that some fixed meteorological tower measurement sites be established and operated to collect a lengthy wind record in this case also.

The measurement of SO_2 or other combustion emission is so expensive, both in terms of hardware and monitoring operations costs, that is should be considered as a tracer species only if sufficient funding becomes available for a "second-phase" or "verification" study where models developed in controlled-release experiments would be verified on actual power plants. However, an investigation of existing SO_2 monitoring data around SO_2 sources in complex terrain may be desirable, and this concept receives further attention below. Measurements at an active power plant would necessitate continuous measurement of relevant stack parameters: SO_2 and/or NO_x stack-mouth concentrations, flow rates, and exit temperatures. These data are available through conventional techniques but are very expensive to obtain. They are essential to any "real-world" study.

Other techniques become useful in measurements on an active plant; Van-based correlation spectrometers can be used to locate plume trajectories and estimate horizontal dispersion parameters. Tetroons should be released to examine valley-flow fields.

Ground-based and airborne LIDAR become extremely useful in mapping plume cross-sections and impingement of the plume with the surface.

4.1 Meteorological Measurements by Aircraft

A light aircraft can be used in the "real world" experiment to supplement the fixed and balloon-borne observations. the principal objectives are the horizontal mapping of the diffusion and the extension of sounding data above the 1 km level, as needed. The latter information, coupled with data from ground-based systems, could provide the needed wind-diffusivity profile for model calculations.

4.1.1 Horizontal Mapping Data. During the horizontal traverses made by the light aircraft to sample the plume concentrations, wind and turbulence data can be gathered to permit horizontal mapping of the plume environment. Such a map would give average wind and diffusivity inputs into the model and would permit an evaluation of the spatial homogeneity of the environment.

Wind and turbulence measurements are made by the aircraft by means of a gust boom, coupled to a gyro or INS system. U , V , W are recorded at a high data rate suitable for processing into (U'^2, V'^2, W'^2) after arbitrary averaging times. Wind measurements are made with the same system.

In the real-world experiment, marked differences in wind and diffusivity environment are expected as the result of terrain influences. The light aircraft offers the potential of exploring these variations within the limits of safe flying. The mobility of the aircraft also permits its use to explore up-wind turbulent influences which may be advected into the experimental area.

4.1.2 Sounding Data. The doppler acoustic radar is expected to provide wind and turbulence profile data to a height of 1 to 1.5 km. At many sites, wind and diffusivity data will be required to a higher elevation. The aircraft can be used to extend the sounding data above the doppler acoustic radar so that a diffusivity-wind profile can be obtained within the plume environment.

U', V', W' measurements, together with an INS or similar system, can provide both wind and turbulence information for construction of this profile. It is suggested that this might best be accomplished by a series of horizontal aircraft traverses (of about 30 sec each) at elevation intervals of 100 m above the acoustic radar. These data could then be processed into profile form and fitted to the acoustic radar data to form a complete vertical profile of wind and diffusivity.

4.2 Tetroons

Tetroons are balloons balanced to fly at a constant-density level. Tracking is accomplished by a tracking radar which records azimuth and elevation at uniform time intervals. Winds can readily be obtained over one-minute time periods at the level of balloon flight.

The tetroon is useful in indicating parcel trajectories and in providing detailed wind measurements along the trajectory. Wind speed accuracies of the order of a few tenths of a meter per second can be obtained.

The tetroon, however, suffers from a few disadvantages. Under strong heating conditions, the constant density surface tends to decrease in above-ground-heights as the surface temperature rises. The balloon trajectory, therefore, may not correspond to a plume trajectory. In addition, tetroon oscillations may occur as the result of the attempts of the balloon to find its appropriate density surface. These oscillations may lead to wind measurements and trajectories which do not represent constant elevations above ground.

4.3 In Situ Aircraft Measurement

It is suggested to measure in situ the horizontal distribution of gases and particulates perpendicular to the plume axis. Typical gases are SO_2 and NO_x (both reactive) and, if desired, SF_6 (inert). Typical aerosol parameters are total particle concentration and light-scattering coefficient. Due to negative electric charges, which the effluent particles acquire during or before exiting the stacks, they strongly alter the atmospheric electric field. This effect can be sensibly and accurately measured with electric field mills.

Aircraft speeds of 50 m sec^{-1} of a light-twin and instrument response times of the order of seconds for direct sensing of particles and gases result in space resolutions of 50 m. The response times of field mills of 60 Hz gives a space resolution of 0.83 m.

Repeated measurements of horizontal distribution at given altitudes result in mean concentrations and in horizontal dispersion parameters (σ_y) of the aerosols and gases. Repeated measurements at different altitudes give the vertical dispersion (σ_z). Repeating these measurements at different distances from the source gives information of the downwind dispersion (σ_x).

Measurements at different geographic locales, or directions of plume movements, provide information of (complex) terrain on plume movements. A comparison of results for a reactive (SO_2) with an inert (SF_6) gives information on the chemical conversion rate of SO_2. Simultaneous changes in the dispersion of fine particles indicate the rate of their formation.

4.4 FM/CW Wind Finding

For this experiment, it might be useful to perform VAD scans with the FM/CW radar at several different zenith angles. When the lowest elevation is used, the winds will be averaged over a circle measuring a kilometer or more in diameter. Then with higher elevations, much finer horizontal homogeneity of the wind field results. As in the smaller scale experiments, the ability of the radar to detect and measure thin shear zones could be most useful.

5. DATA MANAGEMENT AND QUALITY ASSURANCE PANEL

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5. DATA MANAGEMENT AND QUALITY ASSURANCE

1. OVERVIEW

Data management and quality assurance, QA, programs are essential ingredients in the conduct of the field experiment. Though normally treated separately, we recognize the necessity for their integration in the manner illustrated in Figure 10. The illustration shows the major phases of data management and how information is fed-back as a quality control measure.

The first feedback occurs after the routine data review conducted in the field. This review is the focal point of data management and quality control in the field conducted in a near real-time environment. The first review consists of analyzing the data for (1) relevance to the field objectives, (2) planning of future experimental activities, and (3) improper equipment operation. This latter point serves as a basis for the primary QA feedback wherein malfunctions are detected on the spot. Immediate repair action can then be undertaken by the appropriate field personnel.

The second QA feedback occurs during the final checking process. This is normally accomplished off-site at the end of the activities. Its purpose is primarily meant to eliminate bad data or flag questionable data and replace these data with correct values, if possible. Lastly, an independent data review is normally conducted by some user other than the field studies contractor.

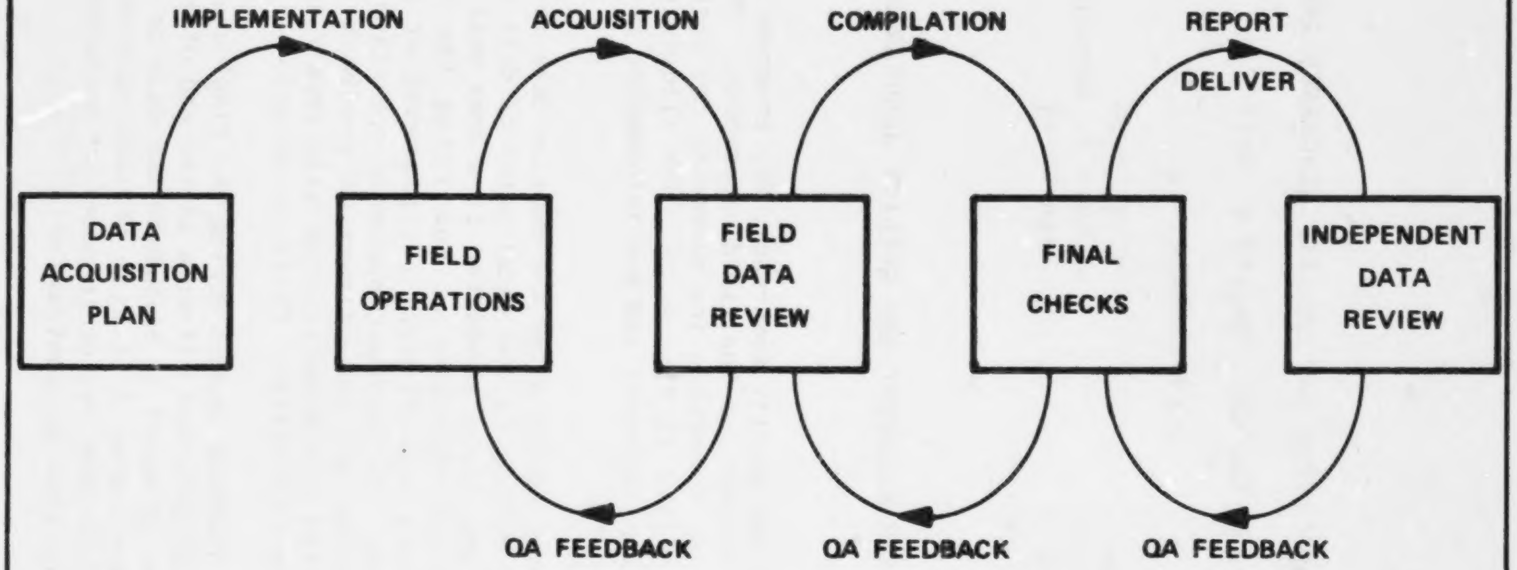

IMPLEMENTATION
ACQUISITION
COMPILATION
REPORT
DELIVER
DATA ACQUISITION PLAN
FIELD OPERATIONS
FIELD DATA REVIEW
FINAL CHECKS
INDEPENDENT DATA REVIEW
QA FEEDBACK
QA FEEDBACK
QA FEEDBACK

Figure 10. Interaction between quality assurance and data management.

In describing the various activities associated with data management, we have distinguished field activities from off-site activities. However, we strongly recommend that both activities be conducted by the same group through the final data archiving process. One exception is our recommendation for independent quality assurance audits conducted by a separate group.

2. FIELD REQUIREMENTS

2.1 Introduction

Requirements for supporting field operations are reviewed for two extremes. On one extreme, only a minimal number of data are required during real-time and other data processing is restricted to rudimentary displays of data. On the other extreme, real-time acquisition, reduction, and display of many parameters are performed; in addition, other tasks are supported such as initial reduction and display of remote sensing data, back-up copying of all data, incorporation of manually entered data, and selective editing. In accordance with Workshop recommendations, we have assumed a two-phase experiment will be conducted. Phase I would be the small hill experiment; Phase II would be a full scale experiment at a power plant site.

The determination of the data processing scheme depends upon (1) the specific requirements of the experiment, and (2) similarities between the Phase I and Phase II experiments. If the Phases are similar, the selected field data system and procedures should be the same for both phases so that Phase I serves as a shake down of the system for Phase II.

Quality assurance procedures remain essentially the same regardless of the complexity of the experiment. However, data review is more easily accomplished with the aid of adequate data display facilities on site. Also, the ability to enter manual calibrations, corrections, or logistical information while still in the field is desired. A small computer system may not support such field entries. Hence, these functions must be performed offsite with perhaps some loss in data integrity.

In the following sections, we describe general requirements for three field functions.

(1) Data Acquisition, Preliminary Reduction, and Archiving -- specifying the forms of data acquisition, what field calculations must be made, and the data product that is generated in the field.

(2) Data Review -- specifying the on-site information required to (a) check the validity of the data in a timely fashion, and (b) to support the planning of future field (experimental) operations.

(3) Procedures and Calibration -- describing the pre-field and field activities required to maximize the quality and integrity of the data.

Lastly, we recognize the special requirements posed by remote sensors. Accordingly, we address these in the last sub-section.

2.2 Data Acquisition, Archiving, and Preliminary Reduction

In discussing the requirement for the field data management system, we have resticted ourselves to generalizations to some extent. The actual requirements are directly related to the complexities of the field measurement plan.

2.2.1 General. The following features are described for most types of field experiments that are foreseen:

- All data should be available in semi-finished form within 12 to 24 hours for experimental planning and review.

- Those data required for decision making and the general management of experiments in progress should be displayed in real time. These data should include sufficient meteorological information to determine if conditions are favorable for the conduct of other measurements (e.g., tracer release). It is highly desirable, but not necessarily cost effective, to display real-time ground-level concentration values. Graphics display of real time is also highly desirable but not necessary.

- All data should be archived in the field in raw form (without necessarily being converted to more usable parameters such as diffusion coefficients, plume height, and so forth); this stage of data reduction and conversion will be reserved for a later time.

- All data should be backed up by duplicate records; data tapes should be duplicated in the field or off-site as soon as possible.

- Strip charts should not be used for the primary data record although they are acceptable as backup.

- Handwritten records of maintenance and calibration teams should be carefully maintained for later use in error flagging, quality estimation, and editing.

- The data archival system should include a quality index technique to flag poor quality data and data that have been edited.

- Certain sensor and system status information (e.g., power critical voltages, flows) should be routinely acquired and entered on the raw data tapes.

- The data acquisition system should include an automatic error flagging system for "obviously" erroneous data (i.e., extreme values or rates of change). This will help to identify and correct malfunctioning instruments.

2.2.2 Different Types of Data and How They Are Archived.

a. Continuous Data. Continuous data are considered to be hard wired (or otherwise transmitted) into a data logging computer that records basic signals representing wind speed, temperature, continuous ground-level concentrations, and so forth. These data should be stored on disk or magnetic tape, automatically checked for errors, and made available for real time display.

b. Batch Data From Self-Contained Systems. Batch data include those data from remote sensors, mobile or remote systems (such as aircraft, tethered balloons, pibals, etc.), and batch processing of bag samples. Some of the data may be available on a nearby real time basis (such as remote sensing systems). Others may not be available for hours. These data will be available in different forms and it is not necessary that they be combined onto a common tape in the field. Care should be taken, however, to insure that all tapes can be easily read by the central, off-site computer at a later date. All data from these various systems should be processed, on-site, to the extent required for program management. For example, lidar data should be processed for examination of trajectories and plume cross-sections. All systems measuring the same thing (such as FM/CW radar, tower wind instruments, and tetroons) should be compared for agreements.

2.2.3 Data Acquisition and Archival System. The configuration of a data acquisition and archival system can be outlined in only a general way until the field data requirements are specified exactly. As a minimum requirement, key meteorological parameters should be displayed and stored on a real-time basis. (If such parameters are to be routinely monitored at times other than during the intensive field periods, it may be cost effective for the field computer to remain in the field. At the other extreme, a more comprehensive computer could be needed to process more real time data, display auxillary remote sensing data, and extensively support data archival. For this more demanding requirement, we estimate that a more comprehensive field mini-computer facility will be required. Peripherals could include a disk, three magnetic tape drives, interactive graphics display terminal (perhaps two), and a high speed (electrostatic) printer/plotter.

2.3 Data Review (Field)

Non-real time detailed review of data is expected to be conducted off-site incorporating final checks of consistency, extreme value and other automated data checking techniques. Final calibration adjustment of data is also expected to be accomplished off-site.

Real-time and near real-time preliminary on-site field review of data is limited to that necessary to determine the proper working order of instrumentation and recording equipment, and that necessary to operationally plan the successful conduct of the experimental program.

Preliminary quality assurance of instrument recording, conversion, and transmission may be accomplished by spot check comparisons of manually reduced analog information and recorded digital information. Computer graphics may be beneficial for reproducing the analog trace for comparison with back-up chart recording. Real-time comparisons of wind and temperature field data for consistency should also be accomplished in the field.

Real-time wind and temperature field data available in the system provides an exceptional operational planning tool. While it is important to assess the possible overriding effect of synoptic weather situations on operation of the experimental program, it is essential also to assess the diurnal effects of topography and temperature gradients as reflected in the wind and temperature field data recorded for the past 24-36 hours. The trends established concerning the timing of drainage flow, the intensity and height of the nocturnal surface static layer, break-up, and wind direction and speed provide good indication of whether the day's activity should be devoted to intensive measurements or perhaps maintenance and calibration and other activities.

Some meteorological and other measurements essential to meaningful description of the wind and thermal field, such as pilot balloon observations, by nature require manual entry into the system for near real-time operational planning. These should be reviewed and compared with other wind data for consistency.

Additionally, it is assumed that sufficient climatological information for the immediate area of concern is made available for operational planning purposes. Such data should be entered into the system for recall and display in a meaningful form by the field program director.

2.4 Procedures and Calibrations (Quality Assurance Program)

This section covers the essentials of the QA program as conducted in the field. Our purpose is to delineate some general (and a few specific) procedures which are applicable to the field preparation and field activities phases of the program which will be useful in assuring data quality. In this regard, it is recommended that a general quality assurance program be activated which will have as its basic elements: (1) review of instrumentation and system specifications; (2) the review of the calibration and operational procedures for the various instrumentation and data acquisition systems; and (3) the independent audit of all measurement and data systems, where applicable. The individual elements of such a recommended program are discussed in the following paragraphs.

2.4.1 Review of the Instrumentation and Data Acquisition System Specification. After the program design is firm, including a preliminary selection of instrumentation and data systems, it is recommended that a review be conducted of the measurement and data system specifications and operational characteristics to determine how well they meet the performance requirements as dictated by the program plan. This analysis should include an evaluation of such specifications as instrument accuracy, resolution, response time, range, minimum detectible limit, environmental constraints and data output configurations as imposed by the program requirements.

Implementation of such a review may be best accomplished by a panel of several people who have collective experience and expertise in the areas as dictated by the final program plan. It should include people knowledgeable in the individual instruments, data systems, and the utilization of such systems in the field environment.

2.4.2 Instrumentation Calibration Techniques Review. Preliminary to the actual field operations, a review of the calibration techniques should be conducted. This should consist of a review of the calibration techniques and procedures as proposed to be used by the field unit for each individual type of measurement and data system. Information should include the frequency of calibration, type of calibration, traceability to an NBS standard, where applicable, and a functional diagram of sufficient detail to allow understanding of techniques employed and identification of major components; a calibration procedure document including an example calibration formation record form, should be included.

Submission and review of these documents should be sufficiently early in the program to allow for revision as required.

2.4.3 Review of Operation of Field Systems Procedures. A field program of the type under consideration may impose several requirements on one or more of the measurement systems. A proposed field system operational plan should be developed which would delineate the expected deployment of instruments, indicating the expected range of environmental conditions, operating modes, use time or duty factor, primary power supply voltage and frequency range expected and the calibration and maintenance schedule.

A review should be made of the expected degree of degradation that these combined factors may have on data quality. Experience in operation of similar instruments under the expected operational conditions is needed to make this assessment.

The effect of electromagnetic interference should also be investigated. Such things as high power radio stations and radar installations can cause noise in the recorded data. This noise may be coupled into the system via electric field interference in high impedence circuits and/or magnetic field coupling through long data or signal lines.

Recognition of this problem and logging of operational information can be very useful in identifying these artifacts in the data.

2.4.4 Measurement System Audits. In-field audits of all measurement and data systems are recommended. Audits should be conducted for both the sensor outputs and key status measurements (e.g., flow rates for collection devices). The frequency of the audits depends on the desired degree of independent assessment of the data quality commensurate with the type of instrument being audited.

Audit procedures for most of the gaseous analyzers, such as SO_2, NO-NO_x, and O_3, have been developed by EPA. A considerable amount of information is available to guide the designer in the expected accuracy and stability of some of the instruments. Audits of meteorological and remote sensor measurements systems are also necessary for this program and some reasonable effort should be expended in reviewing and improving audit procedures for these devices. For some of these sensors "injected signal" techniques should be used where overall performance cannot be verified.

An audit of the data acquisition system should be carried out to determine the correctness of the transfer of the output signal from the respective measurement systems through data processing. This may be accomplished by monitoring the output of the respective sensors for selected increments of time and then comparing these values, which have been independently corrected for calibration functions, etc., and then comparing these data to the output at the central data processor. This allows also for the checking of the proper applicability of all calibration equations and correction factors.

If any unit fails to respond correctly to an audit, an appropriate notification must be made to the Field Director. Every effort must be made to ascertain the cause of the failure and to document the circumstances, duration of the failure (if known), and procedures to correct the data, if possible.

2.5 Special Considerations for Remote Sensors

The following material is keyed to the outline of the panel recommendations. It consists of recommendations for the special consideration that must be given to the data from remote sensors such as radar, lidar, and acoustic sounders. In general, each remote sensor has its own data acquisition system and will provide a computer tape (probably 9-track, phase encoded, 1600 bpi) on which will appear files containing calibration runs, background information, and data.

In the case of ordinary lidar, this data will be backscatter coefficients as a function of range, perhaps with separate files for separate wavelengths and separate polarizations. One or all of these may be present depending on the files. The lidar data must be processed to remove the effect of the inverse square of the range, all drifts must be removed, the zero point identified, and the calibration factor applied. Programs exist to perform these functions. They can be applied by the lidar crew outside regular working hours or the programs may be adapted to use on the field director's computer. Because of the differing formats for tape storage, it is probably most useful to use the field director's computer. Hard copies of graphs of a few shots can be produced quickly by the lidar crew for evaluation of plume spread. After the above, processing data may be displayed, averaged, or otherwise processed.

A Doppler radar (e.g., FM/CW) produces information on backscatter coefficients versus range and the radial velocity versus range. The data is displayed in the field and digitized and placed on magnetic tape. Data processing programs exist and can be adapted to the field director's computer. Increased information on three dimensional velocity fields can be obtained by using dual-Doppler radars. In this case, the outputs of both radars must be combined in a computer; probably the field director's computer must be used because the existing radar computers don't have this capacity.

Acoustic sounders also produce magnetic tapes containing information, on repeated scans, on the backscatter coefficient vs. range, and the Doppler shift versus range. Probably some development of programs is required here because the field director's requirements for display must be considered. The acoustic sounder data is often usefully displayed in a facsimile form to obtain an immediate view of the structure of temperature inhomogeneities. Extraction of acoustic Doppler information is available to present wind velocity vs. height.

2.5.1 Objectives. The objectives of data management for the remote sensors are essentially the same as for other data sources. However, remote sensors are often called on for data to guide the field director in the choice of operating parameters at his disposal. Some of the data must be available in real-time and most of the data must be available for review within twelve hours in a form from which good, but not necessarily final, estimates of relevant parameters can be made.

2.5.2 Requirements.

a. Phase I - The Small Hill Experiment. Probably, at the most, one remote sounder will be present, and only a small computer facility under the field director (part of the remote sensor system). In this case the remote sensor computer must produce hard copy graphs or photos or charts or tables of its output for use by the field director as well as a complete tape record of its data. A sampling of theses must be available in essentially real-time to the director. More complete processing must await transmittal to a central facility.

b. Phase II - Full Scale Experiment. Probably one or two lidars, one or two radars, and one or more acoustic sounders will be employed. The additional complexities of this experiment, and its multiple objectives (depending on weather conditions and where the plume is going) require the same essentially real-time availability of remote sensor data to the director as in Phase I.

2.5.3 Data Review Support. Each remote sensor data acquisition system must possess the capability of automatic rejection of data (non-recording) when the predictable mishaps occur, such as misfires, intolerable power fluctuations or other debilitating failures. This minimizes bad data on tapes. Each remote sensor system must periodically test for correct operation in such a way that the result shows up on the data tape and is identified as a calibration file. The results of these tests must be examined by the computer during processing. The remote sensor operator must also supply standard tests to apply to data while processing. Whenever possible, known physical measurements that test entire systems should be employed. Error estimates must be supplied by the remote sensor crew.

3. OFF-SITE REQUIREMENTS

3.1 Introduction

The general requirements off-site consist of provision for final reduction, completion (i.e., merging, organization, storage, retrieval), final quality assurance checks, and data products useful to the model development and evaluation community. The complexity of this activity is direcctly proporational to the overall complexity of the experiment and what is accomplished in situ, while it is preferred that some final reduction (i.e., conversion and validation) and some compilation is performed in the field, it is recognized that some may be required at an off-site facility. Clearly, a large off-site facility (e.g., EPA's Univac 1110) is needed to store the final archive and thereby serve as a clearing house for future data requests.

The field team should have the primary responsibility for the initial off-site activities because, simply stated, they are most familiar with the data and hence in the best position to validate it. Their participation should continue through the establishment of the final archives.

3.2 Compilation

The compilation phase of data management involves accession of all data collected during the study period and all associated conversion, reduction and error checking. The first consideration is the type and form of the collected data which may obviously be contingent upon the availability of an on-site computer during the experiment. The following is a list of the general data types -- (1) continuously monitored data which can be directly fed into the on-site computer or collected on data tapes; (2) manually reduced data such as lab analysis or pibal soundings; (3) self-contained systems such as Lidar, Sodar or Radar; (4) equipment logs, calibration and audit information; and (5) preliminary analysis and error detection used during the field planning review meetings especially if an on-site computer was available. If an on-site computer was not available during the experiment, some additional conversion equipment (e.g., A-D) may be required for data reduction.

The basic functions during the compilation phase are as follows:

1) Collect all data tapes, logs, etc., and associated documenta-describing format and content of the data tapes. Enter all manually collected data onto the computer.

2) Make backup copies of all original data tapes. Label and store these along with copies of associated logistical documentation. An informative leader at the beginning of each tape should be included.

3) Perform preliminary automatic error checks. Devise a system to incorporate status, calibration, and log book information. Develop preliminary error flagging schemes. Correct obvious errors.

4) Perform appropriate data conversions and reductions to produce raw data in standard file formats. This results in the first level of data archive.

5) Perform required time averaging and preliminary data analysis to calculate intermediate parameters required by the modelers.

6) Design and prepare second level archive which may include merging of certain data sets.

7) Acquire or develop a data management system for simple retrieval and display of the second level archive data.

8) Develop software to produce higher level archives and data products.

In order to perform these functions it is necessary to receive from the modelers a specification of the required temporal and spatial resolution and a list of calculated parameters that are required as input to the model. In addition to data collected during intensive periods, two other types of data must be managed. First, climatological data may be collected for a prolonged period. Procedures must be developed to verify and archive this long term data set. Finally, an effort should be made to obtain all data available from other studies which may shed some light on the complex terrain problem. A method of archiving and retrieving this data should be developed to provide easy access for the modelers. A special effort should be made to obtain and integrate data from the DOE and EPRI studies.

The data management and quality assurance panel recommends that the contractor provide EPA with all original data and at least two forms of the archieved data and associated software so that EPA may act as a clearing house for distributing the data to modelers and other contractors.

3.3 Final Checks and Analysis

One of the principal components of the data management task is to assemble and guarantee a valid, reliable data set to be used by the model developers. Inherent in these tasks are error checking and analysis procedures at three fundamental levels in the chain from field measurement to model development. These levels include 1) Analysis in the field (see Section 2.3), 2) Analysis by the data manager, and 3) Analysis by the modeler after the data set is final. In this section some automatic, computerized, and analyst-invoked error-checking procedures contained in the data base management system (DBMS) are described. The DBMS should include a modular set of error checking procedures from simple range checks to sophisticated numerical techniques while maintaining a human decision factor in any data modification. The system should contain a formal process for updating the data base and reporting all modifications.

Separate procedures can be developed for single and multiple sensor error checking.

3.3.1 Single-Sensor Error Checking. There are five basic error checks for individual sensors:

Range Checks

Rate of Change Checks

Calibration Analysis

Outlier Detections

Time Series Forecasting Techniques

The first two can be computerized to provide an automatic method for flagging potential errors in single-sensor data. Range checks include searching for both certain and possible errors: For example, include negative air quality concentrations. Possible errors can be determined by comparing the measurements with established climatological or "reasonable" values. For example, solar radiation data should follow a diurnal cycle and exhibit a reasonable daytime maximum. Similarly, maximum daytime temperatures at a particular locale should not exceed 35 degrees C, for example. The temporal rate of change of selected variables can be compared to probable maximum rates, e.g., a temperature change of 10 degrees/hour. Similarly, most operational instruments display certain small random changes. If these are not exhibited in the data, it could indicate a stuck or frozen instrument, excluding those with natural constant states, e.g., zero air quality measurements.

Analyst invoked (manual) error checks could include an examination of the calibration history of an instrument. Rapid changes in calibration constants are probably indicative of malfunctioning instruments. Unfortuantely, it may be necessary to apply nonlinear correction factors to recover valid data. Outlier detection procedures include polynomial or spline curve fitting to the time varying data points. Most real aerometric data samples should reasonably approximate the predicted curve (Figure 11). Outliers from the predicted curve could indicate incorrect samples which could be corrected by the "predicted" values. (Such corrected values must be flagged accordingly in the data record). Time series forecasting techniques include trace analyses (useful for determining drifting calibrations) and principal component analysis. Table 2 summarizes some of the available single sensor error checks.

TABLE 2. SINGLE-SENSOR ERROR CHECKS

Automatic	
Range	$SO_2 > 0$
Rate of Change	$\frac{\partial T}{\partial t} < 20^{\circ}C/hr$
Manual	
Calibration	Spline Fits
Outlier Detection	Polynomial Fits
Time Series	Fourier Fits
	Baseline Offset
	Trends

3.3.2 Multiple Sensor Error Checks. Again, multiple sensor error checks can include both automatic and analytical procedures. Some of the automatic checks include a comparison of pairs of data to established identical or probable physical relationships, e.g., $NO_x = NO + NO_2$; $T \geq T_D$. Statistical relationships derived from climatological data can be used to isolate low probability events that can be flagged for further examination. Manual checks of multiple sensor data can include graphs, tables, scatter diagrams, line plots, contour diagrams and perspective plots. These simple exhibits for visual pattern recognition will enable the rapid evaluation of the data.

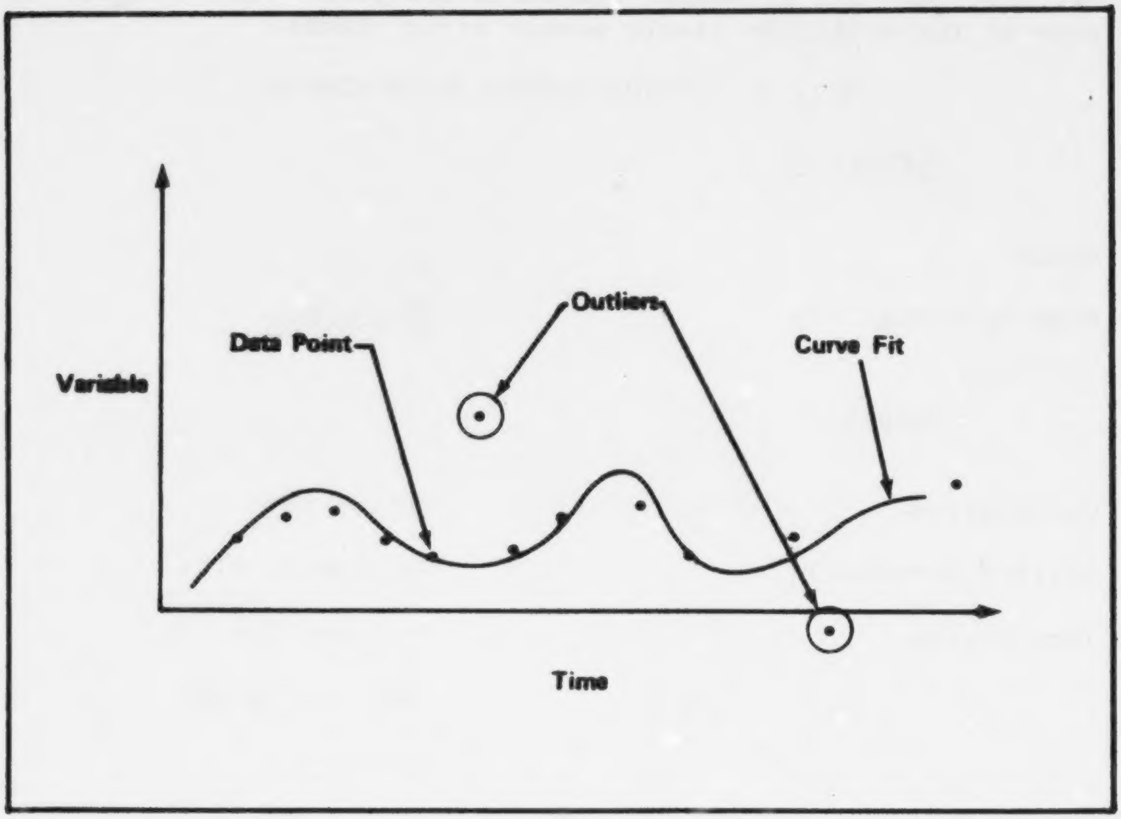

Outliers
Data Point
Curve Fit
Variable
Time

Figure 11. Example of outlier detection.

3.3.3 Update Procedures. The simple automatic analysis-invoked error checks should be designed to detect possible errors. Only the analyst should be allowed to actually change a suspect value. Each change should be identified in a report and in the archive, as follows:

New Value

Date/Time of Change

Old Value

Reason for the Change

Values that are suspect and not changed in the archive should be flagged (according to a prescribed code) for the modelers' information. The updated report then becomes a permanent part of the data archive.

3.4 Data Products

There will be three basic data products coming from each experiment including an archive of raw data, a model development (and analysis) data set and a summary report describing the data. The data archive will be a corrected and edited compilation of all data acquired in the field program. It will be available in total and in subsets without further processing to meet requirements not met by the model development data set. The model development data set will include such parameters as are needed for model development, evaluation and diagnosis, which are specified prior to and in the course of the program. The parameters will be averaged over specified times and will include values derived from combinations of archived values, such as plume spatial distribution parameters σ_y and σ_z and various stability parameters. The summary report will describe the experiment, the types of data available, the accuracy of the data (as indicated by audits and parallel measurements), and a quantitative summary of the data available in each intensive period.

Another data product will be processed data from other field studies. It is desirable to prepare data from other field studies at least for model evaluation if not also for model development efforts.

3.4.1 Data Archive. An archive of raw data should be maintained so that it is available for special purposes not foreseen in the present study. Selected subsets for designated time periods or observation systems should be available on request. The volume of data can be condensed by eliminating useless data, e.g., lidar scans which do not intersect the plume and which are not required for background data. The archive will be edited and corrected for instrument calibration and audit results so as to contain the best possible measured values. The contents and organization of the archive should be described in the summary report.

3.4.2 Model Development Data Set. A model development data set should be derived from the archive to meet the specified requirements of model developers and model evaluators. This data set will be significantly reduced in volume from the data archive to be convenient for data handling purposes. The parameters will be averaged and otherwise characterized over the period of interest. Specified parameters will be derived; e.g., ground lidar observations could be transformed into cross-sections of hourly mean back scatter for fixed distances from the source. Each cross-section could also be characterized by a center of mass position and $_y$ and $_z$ values. Similarly, wind observations can be transformed to mean values and specified turbulence statistics. Any number of stability indices can be computed and placed on the file. It's desirable that modelers be given parameters expected to be useful to fit a priori model concepts and to be useful to diagnose why the expected concepts do not work.

A program must be developed to create the model development set. In view of the complexity and variety of types of data anticipated for use in the planned programs, it is recommended that on the order of 6 person-months be allowed for development of this program. A modification of the program used to generate the model development data set could be used to process data from other field studies in complex terrain. The primary modification would concern interfacing with different data formats.

3.5 Summary Report

A summary report should be prepared to describe the data in order to help modelers and others who deal with the data to select portions of the data and to comprehend its scope. The report should include at least the following

- DESCRIPTION OF THE EXPERIMENT
- HISTORY OF FIELD ACTIVITIES
- TYPES OF DATA RECORDED

- SAMPLE DATA RECORDS
- SUMMARY OF INTENSIVE OBSERVATION PERIODS
- SUMMARY OF MODEL DEVELOPMENT DATA SET
- CONTENT AND ORGANIZATION OF ARCHIVE DATA SET
- DESCRIPTION OF QUALITY ASSURANCE, EDITING AND DATA REDUCTION PROCEDURES
- ESTIMATES OF UNCERTAINTY AND ACCURACY ASSOCIATED WITH EACH MEASUREMENT

The effort required to summarize data is highly dependent on the volume of data required. However, the summary is not expected to be a major part of the data management and quality assurance effort. Perhaps 5 percent of the overall data management effort should be allocated to generating a summary.

4. COSTS

Costs are proportional to the complexity of the experiment, requirements of the field crew, requirements of the model developers and evaluators, and the number of intensive field periods. For our purposes, we have assumed an upper-bound of likely requirements for two field study periods. It should be noted that once the data management software and QA procedures are established for one experiment, costs are much less for a second similar experiment.

In general, we anticipate that 12 to 13 person-years will be required for the two phase approach suggested by various panel members. Personnel and support costs (i.e., travel and subsistence, report reproduction, miscellaneous supplies) could consume about one million dollars. Taking into account the need for a field data facility (about $130,000) the above costs are consistent with general estimates that data management and QA costs each account for about 10% of the total budget. If Government Furnished Equipment is available for the field data facility, the above $130,000 data facility estimate can be reduced accordingly.

5. OTHER RECOMMENDATIONS OF THE PANEL

During the course of the Workshop the panel became quite concerned that the experiments would not satisfy the primary objectives to improve modeling in a complex terrain setting. Specifically, a better understanding of plume impaction is desired as a first priority. Towards this goal, field studies are planned to collect the necessary data which will enable us to refine existing or develop new and improved model formulations.

Other panels have presented details and recommendations on the above topics. They describe alternatives to achieving the stated objectives. However, our panel would like to address some of the issues. In particular, we would like to express the need for a consistent approach in the follwing two areas:

1. The measurements should be consistent with the need to improve the model in settings of complex terrain. Therefore, we need measurements to verify model performance (observed air quality concentrations) and to verify our estimations of certain intermediate derived parameters. In particular, if we are considering Gaussian models, there is a need for measurements of the vertical and lateral spread of the plumes as a function of downwind distance (or time). There is also a need to measure the flow characteristics of the plume in the vicinity of the terrain obstacle as well as upwind and downwind.

Flow visualization is one means of describing the above parameters and is essential in our opinion. If we rely solely on measurements of ground-level tracer concentrations and conventional meteorological parameters, we fall into the pattern of many previous field experiments whereby we obtain answers for a specific regulatory problem but fail to sufficiently enhance our understanding of the basic processes that are occurring.

2. The scale of the experiment shoud be consistent with our ability to measure the required parameters. We support the concept of first conducting a simple experiment, fixing certain parameters (i.e., height of the plume, source strength, and characteristics of the obstacle). However, having gone to this trouble, it seems only appropriate that we adequately measure other non-fixed parameters to the extent practical. In this respect, the scale of the experiment should be consistent with measurements needed to parameterize the model input parameters (e.g, meteorological tower measurements), verify model predictions (e.g., ground-level tracer concentrations), and verify parameterizations within the model (e.g., visualization of plume spreading and flow patterns).

3. It is essential to develop a method of routine meteorological monitoring to characterize plume dispersion in rough terrain. In

principle, wind speed and direction, turbulence data (vertical and lateral), and mixing height are sufficient (assuming adequate spatial resolution). Of course, there is the problem of relating turbulence data to the plume dimensions. The horizontal wind direction variation, σ_θ , may be appropriate for quantifying the lateral plume dimension, normally quantized as σ_y. For quantifying the vertical plume dimension, σ_z, we may wish to consider measures of the vertical wind variation such as σ_y, or more likely indicies that take into account the vertical differences in wind and temperature (e.g., Richardson number). In complex terrain, the above parameters will be more difficult to measure adequately. Hence, one of the principal outcomes of the experiment should be recommendations of the number and type of meteorological monitors to be used in routine complex terrain assessments.

APPENDIX A

PRE-WORKSHOP MATERIAL PREPARED BY EPA

During the early stages of planning for the Workshop, EPA personnel in the Meteorology and Assessment Division in Research Triangle Park began preparing scenarios on various field study approaches. The first "strawman" plans were prepared by Mr. George C. Holzworth, Chief, Geophysical Research Branch, and Dr. William H. Snyder, Chief, Fluid Modeling Section; Holzworth's plan addressing a full scale measurement program and Snyder's plan a small (100 m) hill experiment. Subsequently, both scenarios were combined into one "strawman" plan and distributed to the Workshop participants for their consideration.

A third document was prepared by Dr. Robert G. Lamb of the EPA Atmospheric Modeling Sciences Section immediately prior to the Workshop. It was distributed during the Workshop for consideration with the other scenarios.

These "strawman" plans are presented below in the same format as distributed to the participants for use as reference material to the panel statements and recommendations presented in Section 5. They should be considered strictly in light of their original intent, namely to provide the panel members with specific ideas and suggestions for deliberation and not as documents intended for publications which have been subjected to editorial reviews and corrections.

PROGRAM PLAN FOR DEVELOPMENT OF A MATHEMATICAL AIR QUALITY ASSESSMENT SYSTEM FOR USE IN COMPLEX TERRAIN

BY

GEORGE C. HOLZWORTH AND WILLIAM H. SNYDER

1. INTRODUCTION

Mathematical models of atmospheric dispersion are relied upon heavily to evaluate compliance with air quality standards and prevention of significant deterioration. Although the economic consequences of model results can be very large, it has been difficult to demonstrate that available models have a reasonably high degree of reliability, especially in regions of complex terrain. This chronic problem is becoming acute as energy development and utilization expand in mountainous areas. The total problem is overwhelming, not only from its complexity of meteorological conditions and terrain configurations that occur, but also from the expense of obtaining adequate experimental data.

The Meteorology and Assessment Division (MD) of EPA's Environmental Sciences Research Laboratory has been charged by the EPA with the development and execution of a five-year, multi-million dollar program designed to produce atmospheric dispersion models that are applicable to large sources in complex terrain and that have a demonstrated higher degree of reliability than existing models. Current (preliminary) plans for carrying out this charge are contained in this document, which will be presented to a Workshop of invited experts during July 16-19, 1979. The Workshop is directed to make recommendations for improving this plan. Some components of the program plan have been adopted from the recommendations of the ERDA Workshop on Research Needs for Atmospheric Transport and Diffusion in Complex Terrain (Albuquerque, 1976).

2. PROBLEM

Reliable mathematical formulation of transport and diffusion of atmospheric pollutants has proven to be an extremely difficult task. For example, for individual plumes emitted under the relatively simple and optimum situation of flat terrain and steady meteorological and emission conditions, model validation of ground-level, maximum, one-hour average concentrations at downwind distances to several kilometers is generally within a factor of two. But for complex terrain settings, where many large individual sources are locating, simulation model results sometimes are not within a factor of ten of measured concentrations. This happens because of (1) the distortions in air flow, (2) the distortions in turbulence that occur in the vicinity of terrain obstacles of all sizes, and (3) because terrain-level concentrations are highly sensitive to the height above underlying terrain of the maximum concentrations in the plume (i.e., at plume center line). These three terrain effects are basic to the overall problem.

The first basic effect of irregular terrain on atmospheric dispersion (i.e., transport and diffusion) deals with the transport, knowing where the plume is located in three-dimensinal space and time. While it is obvious that air must go around or over obstacles (the latter typically during stable atmospheric conditions and the former more readily during unstable/neutral conditions), terrain features also commonly influence the local circulation through the diurnal cycle of heating and cooling that occurs at the ground-air interface. During daytime, upslope flow is enhanced over sun-facing terrain and downward motion is favored over shadowed areas; during non-cloudy nights, downslope flow is enhanced over elevated terrain in association with the development of strong temperature inversions. Under weak large-scale flow conditions these ground-based flows, which vary in depth from tens to hundreds of meters, induce counterflows aloft. With moderate large-scale conditions the flow aloft resembles that of the large-scale, and with sufficiently strong large-scale conditions, the low-level, thermally-induced flows are likely to be overwhelmed or markedly modified by the large-scale flow. In addition, during certain conditions with critically fast winds, terrain features can induce aerodynamic effects which distort the usual three-dimensional flow in the vicinity of the terrain obstacles.

The second basic effect of irregular terrain on atmospheric dispersion concerns the extent to which turbulence and diffusion are altered from their values over uncomplicated terrain. Recent limited investigations in mountainous regions have demonstrated that the Gaussian diffusion parameter values, which are often expressed as a function of the Pasquill-Gifford stability classes, are generally larger over complex terrain than over flat terrain, especially during stable conditions and at relatively short downwind distances from the plume source. But these differences are not necessarily in the same proportion for the horizontal and vertical components of diffusion. The appropriate diffusion parameter values likely depend upon the details of the complex terrain, not only over the terrain beneath the plume but also upwind of the plume source. Furthermore, the diffusion parameter values are expected to vary with height above the terrain, at some level decreasing to the corresponding values for flat terrain.

The third basic effect of irregular terrain on dispersion is in reality a combination of the first two; it concerns the small-scale features of plume interaction with a terrain obstacle in the immediate vicinity of the obstacle surface; it involves transport and diffusion, but for practial purposes at some close distance of plume approach to obstacle surface the transport becomes indistinguishable from diffusion. This effect is particularly important because of the frequency with which plume center lines (where concentration gradients are relatively large) abruptly approach terrain obstacles. For example, a fundamental issue among modelers is the extent to which plumes, that are well above the ground where they are emitted, interact with higher terrain at downwind locations. Various models (e.g., Valley, Cramer, ERT) that have been adapted/developed for use in complex terrain handle this situation by maintaining the plume center line at 1) a constant height above sea level, or 2) a constant height above the underlying terrain, or 3) a variable height above the terrain that is some fractional value of the height difference between the terrain at the source and beneath the plume trajectory; the use of these techniques usually depends upon atmospheric stability. For the case of a plume within a temperature inversion, technique (1) results in relatively very high concentrations, technique (2) ignores the terrain, and technique (3) produces intermediate results. The technique that is most appropriate remains controversial because adequate, full-scale field measurements have not been made.

Some additional questions that may be posed about terrain effects on dispersion are:

1. What are the maximum concentrations on a terrain obstacle that is in the apparent path of and at a higher elevation than a plume embedded in an unstable or neutral layer, with or without an inversion aloft?

2. How do terrain features affect "diffusion coefficients", σ_y and σ_z?

3. In what manner does complex terrain affect mixing heights?

4. How does complex terrain affect plume rise?

Answers to those questions are likely to depend upon the wind fetch over irregular terrain, the details of terrain features (e.g., variously inclined hills and ridges, individually and in combination), atmospheric stability, wind speed, and plume height with respect to that of terrain features.

Clearly, the total problem of understanding and modeling atmospheric transport and diffusion over complex terrain is extremely difficult, but not unsolvable. With the resources that are emerging to support such a research program and the wisdom of the scientific community, we believe that a very significant impact on the problem can be achieved over the next few years.

3. SOLUTION STRATEGY

At this time it seems inappropriate to tackle the total problem in detail, but rather to focus on modeling individual phenomena. In this approach each phenomenon modeled may be viewed as a module of a Mathematical Air Quality Assessment System (ultimately, it would be desirable to have a single equation appropriate to all phenomena modules, but such an approach here appears premature).

As its first priority module the TEB proposes to model the one-hour-average, ground-level concentrations that result from plume impaction on elevated terrain. More specifically, we mean "fanning" plumes (i.e., within a temperature inversion) that encounter a terrain obstacle(s). This phenomenon has been difficult to model satisfactorily and has occurred often in assessing the satisfaction of air quality requirements. The focus is on maximum terrain-level concentrations since typically they occur relatively closer to pollution sources than lesser concentrations, and therefore are easier to study and model. The model that is to be developed must have demonstrated reliability and specified applicability; it must be reasonable to apply in terms of computer resources and required meteorological input information. However, because meteorological conditions are more variable over complex than flat terrain, it is likely that for a given degree of reliability, complex terrain models will require more meteorological input than comparable flat terrain models, and than currently is available in most real situations.

We propose to develop this modular model from the results of field experiments which are essentially on two scales and which are briefly described here:

1. A small hill about 100 meters high in otherwise uncomplicated terrain would be highly instrumented to measure meteorological variables and the concentrations from a movable tracer source. This experiment essentially would expand into the real atmosphere the scale of laboratory fluid modeling that has been done by Hunt et al. (1978).
2. Full-scale field measurements would be made of meteorological variables and pollutant concentrations from an operating power plant in complex terrain. Tracer studies on terrain obstacles in the vicinity of the power plant would be employed also. This experimental strategy is intended to provide a direct link between idealized experiments and actual operating situations.

It should be emphasized here that model production is the objective of this effort. While the required model(s) clearly cannot be developed with inadequate experimental information, the necessary experiments must be kept within bounds that assure adequate resources for model development and evaluation. We believe that our modular approach to the total problem provides a means of achievability within available resources and it provides a logical basis upon which to build if additional resources develop.

4. IMPACTION MODULE DEVELOPMENT PLAN

Since model development is paramount in this effort, the modelers must be active throughout the project. They must specify requirements for measurements early in planning experimental operations; they must be involved in archiving and documenting the data to assure that their requirements are being met; and they must be immediately involved in the experimental data analyses in order to thoroughly understand the results for effective incorporation into future experiments and inclusion in the mathematical models that are under development.

A. Field Study Design

Experimental field studies will be carried out in three designs in order to quantitatively establish the process of plume impaction.

1) Small Hill Tracer Study. This study will provide a tie-in between the real atmosphere and the laboratory, scaled, fluid modeling studies that have been done by Hunt et al. (1978). Meteorological conditions and the impact of an inert tracer plume will be measured on a three-dimensional hill, no higher than 100 meters and located in

otherwise flat terrain. The tracer (e.g., ethane, SF_6, etc.) will be dispensed from a portable tower or tethered balloon. About five 150-meter towers, instrumented at several levels, will be placed around the hill and a shorter tower will be positioned on top of the hill. All monitoring data will feed directly to a central minicomputer for immediate analysis and real-time graphical display so that source location, height, and strength can be altered to achieve the desired impaction characteristics. This study is designed to enhance the acquisition of data by simplifying the logistics and terrain complexities; it differs from the laboratory studies of Hunt et al. by necessarily including the turbulent boundary layer next to the hill surface that occurs in real situations.

Meteorological measurements would be made of the three-dimensional wind, temperature, and other variables that the modelers may specify. It is estimated that tracer samples will be required at about eight levels on the hill.

The hill size required for this experimental study and for general applicability of the results is not believed to be important, except the hill should be completely immersed in a very stable layer, the hill should be large with respect to the surface boundary layer depth, and the ratio of hill base-diameter to height should not exceed eight. Theoretically, the flow structure will be dependent upon the Froude number

$$F_r = U_h \div \sqrt{gh\Delta T_h/T}$$

where U = wind speed, h = height, g = gravity, and T = temperature. If the vertical temperature gradients and velocity profiles are linear, which frequently occurs, the Froude number is independent of hill height. Thus, the entire range of atmospheric stability variations may be obtained by performing the experiments on a single hill, one perhaps even smaller than 100 meters high.

We believe that a large and adequate amount of experimental data can be obtained during about three months of field operations after the equipment is set up.

2) Full-Scale Plume Study. This study is designed to link the idealized, small-hill, experimental results with those focused on the plume of a large operating power plant. The principal pollutants to be measured will be SO_2 and total particulates, including sulfates, which will permit calculation of the sulfur budget. SO_2 transformation over travel times up to a few hours, however, is not expected to be significant. While pollutant transformations and

depletions are important factors to be included in comprehensive models, they need not necessarily be studied in complex terrain, and are under study elsewhere. The measurements of total particulates and particle-size distributions in the plume will be especially useful in conjunction with lidar measurements of plume configurations. Measurements of meteorological variables, SO_2 and particulate concentrations will be made from ground-level and aloft through the plume, using sophisticated (but currently available) and conventional sensors carried on mobile and fixed platforms as necessary to define plume configurations and meteorological conditions. For ease of operation it is desirable that potential plume impaction terrain obstacles be relatively close to the power plant, preferably within 25 kilometers. Candidate power plants for this full-scale experimental study should be screened carefully for the desired terrain features and meteorological conditions. In addition, the operators of the power plant(s) selected for study must be willing to cooperate completely since pollutant emission rates, effluent temperature and volume-flow rates, other chimney/plant characteristics, and meteorological conditions in the immediate vicinity of the plant must be known continuously during field measurement experiments.

SO_2 may be measured remotely by the Barringer correlation spectrometer method and directly by readily available, EPA reference methods; particulate aerosols can be measured indirectly by lidar and directly by light scattering (nephelometer) as well as by conventional filtering techniques. Although accurate measurements of particulate concentrations over short-time intervals are difficult, the main reason for requiring them is for tie-in to lidar measurements of plume configuration.

Meteorological measurements will require several towers extending to about 50 meters. Besides the usual measurements of transport and turbulence, the fluxes of heat, momentum, and moisture would be determined. Indirect measurements of wind fields would be made by doppler acoustic or laser techniques. Frequent double-theodolite pibal and temperature soundings would be required. Consideration would also be given to the use of acoustic sounders to record growth and decay of nocturnal temperature inversions. Several aircraft would be used not only for plume sampling and meteorological measurements, but also for servicing and transporting mobile ground-based equipment.

This full-scale study will be conducted intensively during four- to six-week periods of at least one winter and summer season and at other power plants in succeeding years as necessary and dependent on available resources.

In conjunction with the full-scale plume measurements, tracer studies will be conducted in order to optimize the measurements of impaction on terrain obstacles in the vicinity of the power plant. These experiments will also be used to resolve complex, site-specific questions about modeling assumptions and to broaden the range of applicability of the results. For the most part we expect these tracer experiments to be carried out when transport conditions are inappropriate for full-scale plume measurements, although in some situations they may be extremely useful in augmenting the full-scale measurements.

B. Laboratory Simulation

Careful consideration needs to be given to the further use of laboratory scaled (physical) modeling techniques to complement the field studies and model development. This relatively economical tool can provide essential detail and data for correlation with and extension of computational model development, field investigation, and definitions of basic aerodynamic characteristics. For example, it would be extremely useful to model specific terrain features in the vicinity of the plant(s) selected for study, as well as in the vicinity of other plants. Such laboratory modeling would also be used in developing mathematical modules of other important plume phenomena such as "fumigation" and "trapping".

This effort could be performed at ESRL's Fluid Modeling Facility at Research Triangle Park, especially in view of that group's contributions and on-going interest in the overall problem as well as the administrative convenience of being co-located with the MD.

C. Potential Field Sites

From practical considerations it will be desirable to conduct the small hill tracer study in the vicinity of the power plant selected for full-scale study, although this approach should not be pursued to the extent of compromising the basic requirements for the small hill experiments. In any case, it is believed that an appropriate site can be found without great difficulty.

For the full-scale plume study, the specific details of the experiments would be designed around the power plant that is selected for study. A prime factor in this selection must be the willingness of the plant operators to cooperate. At the present time, because of anticipated energy resource development and utilization in the West and because of presently operating plants that are relatively isolated from one another, a western plant is favored for the initial study.

As points for discussion, two possible power plant sites are described. However, their potential for plume impaction on elevated terrain should be studied further. The Navajo Power Station near Page, Arizona, is an example of a power plant on a plain with nearby prominent terrain features. With a capacity of 2250 MW, Navajo has three 236-meter stacks that emit about 200 tons/day of SO_2. The plant elevation is 1300 meters MSL, and there is a variety of terrain irregularities within 30 km. At their closest point about 22 km west, the steep Vermillion Cliffs and the plateau behind them rise to around 2000 meters; the cliffs trail off to the southwest and northwest for 10-15 km. There are numerous singular peaks fairly close to the plant, e.g., Lechee Rock reaches 1800 m at 7 km to the southeast and Tower Butte is almost 1600 meters in elevation at 10 km to the northeast, as well as other obstructions at greater distances. The terrain in this region is so rugged that many locations cannot be reached by surface vehicles. This site has good potential for studying plume impaction as well as other types of plume interactions with individual terrain features.

The Mohave Station, on the Colorado River near Bullhead City, Arizona, is an excellent example of a plant in a very deep and broad valley. This plant has a capacity of 1500 MW and emits about 44 tons/day of SO_2 from a single 150-meter stack. The plant elevation is 200 meters MSL and the terrain generally slopes up to the east and west of the north-south Colorado River, reaching 900-1200 meters within 15-25 km. There are also numerous smaller terrain features within 30 km of the plant. The weather at this site is dominated by a diurnally varying mountain-valley circulation, which could serve as the focus for field experiments. With suitable large-scale flow, aerodynamic effects on the plume are expected. During summer, temperatures well above 100°F are common at Mohave and likely would cause some problems for field operations.

It should be mentioned that both these sites are in the southern Rockies where moisture is sparse so that precipitation depletion of the plume and SO_2 tranformation (as enhanced by high humidity) would be small. Furthermore, the infrequent occurrence of precipitation is highly desirable for field operations.

The question arises whether to conduct the complex terrain plume study intensively at only one location for the study duration, or whether to progress to a second (and maybe third) site based on terrain peculiarities. While it would be highly desirable to operate at two or three different sites in order to increase the general applicability of the models developed, resources might not be sufficient to allow this portability at the anticipated funding level.

D. Model Development and Testing

For emphasis, it is mentioned again that the models to be developed must be reasonable to apply in terms of required computer resources, input meteorological and plant operations data, and other information, and the models must have demonstrated reliability. Since production of mathematical models is the basic objective that drives this project, the modelers must be active in all phases. They must prescribe the initial modeling approach and the required input variables (including any new but practical concepts); they must participate in field study designs so as to build upon earlier results; they will be responsible for field data analyses/interpretation and for incorporating them into the modules of the air quality assessment system that they are developing. The models will be tested for sensitivity to dependent parameters, validity of calculated concentrations and transferability to other complex terrain settings. In addition, comparisons will be made to "off-the-shelf" models (e.g., EPA's Valley and CRSTR models and Environmental Research and Technology's variable height model), as well as to other models under development, in order to demonstrate modeling accomplishments.

At this point in time it seems unlikely to expect the emergence of basic new modeling concepts. Rather, the Gaussian distribution of time-averaged concentrations within the plume is expected to persist, but with distortions and modifications, due to terrain, somewhat as modeled now but supported by experimental data. Perhaps the concentrations can be calculated in successive phases of dispersion as effected by classes/types of underlying terrain. For example, plume impaction on elevated terrain is likely to be a function of the maximum terrain-level concentrations within the plume just before it significantly interacts with the terrain. Thus, the plume centerline concentrations could be calculated in the first phase much as in the usual manner and the terrain-level, impaction concentrations in the second phase by consideration of the terrain characteristics.

Because of terrain effects, it seems clear that considerable effort will be required to adequately model plume paths, particularly at greater distances from sources. It also seems likely that more input information will be required to satisfactorily apply the models than is normally available in complex terrain. In terms of input data, consideration should be given to using them to generate reliability factors in the model applications. For example, wind fluctuation and/or other meteorological measurements, taken over appropriate averaging times, may be indicative of the reliability of the estimated plume location as well as the diffusion rate. Diffusion rates, as functions of terrain features, height, and stability probably will have to be determined experimentally as in the past.

E. Complex Terrain Modeling Workshop

During July 16-19, 1979, a Workshop (conducted under an EPA contract with North American Weather Consultants) will be held in Raleigh, North Carolina for the purpose of commenting and developing further recommendations on the program plan presented in this document. About 45 participants have been divided into five panels:

1. Model Development and Analyses
2. Model Evaluation and Application
3. Experimental Design
4. Measurement Techniques
5. Data Management and Quality Assurance

The final report on the Workshop recommendations is due from the contractor in September 1979, for subsequent publication and distribution. An initial draft of the document is expected at the close of the Workshop.

F. Schedule and Budget

A schedule of research milestones appears on the following page. Notice that the modelers will be active throughout the project. The small-hill impaction study will be conducted at only one site, as presently conceived, although such studies of other plume configurations might be warranted at a later time. Full-scale plume impaction studies would be continued as necessary, although we believe that after one year sufficient progress will have been made to focus on other modules (plume phenomena) of the assessment system. The first year's (FY-80) resources are expected to produce fundamental results based on the small-hill tracer impaction study. Continuation into the full-scale plume measurements will depend upon continuing resources. Assuming funding of approximately 2 million dollars per year for three years (beginning in FY-80; to be expended over about five

SCHEDULE OF ORD RESEARCH MILESTONES FOR DEVELOPMENT OF DISPERSION MODELS IN COMPLEX TERRAIN

(ASSUMING RESOURCES BEYOND FY-80)

JUL 1979 - CONDUCT WORKSHOP TO GENERATE RECOMMENDATIONS FOR RESEARCH THAT WILL PRODUCE SCIENTIFICALLY SOUND DISPERSION MODELS FOR SOURCES IN COMPLEX TERRAIN

SEP 1979 - WORKSHOP REPORT FROM CONTRACTOR

DEC 1979 - ISSUE RFP BASED ON WORKSHOP RECOMMENDATIONS

APR 1980 - SIGN INITIAL CONTRACT (WITH OPTIONS TO BE EXERCISED DEPENDING ON PROGRESS AND RESOURCES)

PLAN MODEL DEVELOPMENT, FIELD STUDIES, AND SCALED PHYSICAL MODELING; DO MODEL DEVELOPMENT AND TESTING

APRIL 1980

CONDUCT SMALL-HILL IMPACTION TRACER STUDY
JAN 1980-DEC 1980

PUBLISH RESULTS (PERTINENT TO PHYSICS ASSUMED IN VALLEY AND OTHER MODELS
JUN 1981

INITIATE FULL SCALE FIELD STUDIES PROGRAM
JUN 1980

CONDUCT FULL-SCALE PLUME IMPACTION FIELD STUDIES
JAN-FEB 1981

JUL-AUG 1981

JAN-FEB 1982

PUBLISH INITIAL RESULTS OF MODELING IMPACTION
APR 1982

JUL-AUG 1982

PUBLISH REFINED RESULTS OF MODELING IMPACTION
DEC 1982

CONTINUE FULL-SCALE FIELD STUDIES IN 6-MONTH INTERVALS, POSSIBLY AT ADDITIONAL SITES AND FOCUSING ON OTHER IMPORTANT PLUME-TERRAIN INTERACTION PHENOMENA

1985

PUBLISH MODELING RESULTS AS SOON AS POSSIBLE TO COMPLETE years), we believe that significant progress in the development of a complete model assessment can be demonstrated.

G. Management and Implementation

Responsibility for directing this complex-terrain, plume-modeling study has been assigned to ESRL's Meteorology and Assessment Division. A high-level steering committee will be formed to provide overall guidance toward program goals, to monitor progress at frequent intervals, and to provide a liaison between the program and the user community. In addition, an in-house working group composed of modeling and measurement subcommittees will be available to MD personnel to help assess the validity of the modeling effort and to assist in reviewing technical proposals and reports.

As presently foreseen the entire program plan will be carried out under contract, probably with a prime contractor responsible for the overall modeling effort and with provision for subcontracting. Monthly progres reports from the contractor will be required and will form the basis for reports/presentations to keep the steering committee informed of program accomplishments and immediate plans.

5. DEVELOPMENT OF OTHER PLUME-TERRAIN INTERACTION MODULES

Although this model-development program plan has focused on the important plume-dispersion phenomenon of impaction on elevated terrain, it is appropriate to point out for completeness that models for other plume phenomena may be developed through the same basic approach; that is, through laboratory scaled physical modeling (as appropriate), tied in with full-scale plume measurements.

Data collected in the full-scale field study will be useful for this purpose. Reference to the schedule shows that the program is designed to implement the small scale hill study first and to initiate detailed planning for the full scale field study at the same time. The full scale field study will be initiated in late FY-80 and will overlap the conduct of the small scale studies.

The site selected for the full scale field study will be selected to maximize the opportunity to incorporate the findings of the small hill study and to maximize the opportunity to collect data useful for developing other modules of the final model equation.

Two major areas of uncertainty by the presence of complex terrain are the transport wind field which may vary significantly over small distances, particularly in the vertical direction and an altered turbulence field which may drastically affect the dilution rates. Thus, the long-term goals of the modeling program must consider a satisfactory description of the transport wind and turbulence fields as well as the joint frequency of occurrence of a wide range of meteorological conditions and topographical configurations. The frequency with which certain events occur, are of course pertinent to the question of whether or not the Air Quality Standards are violated and must therefore also be studied. A separate document has been prepared by Dr. Robert Lamb which addresses the frequency question and will be available to participants at the Complex Terrain Workshop.

COMMENTS AND SUGGESTIONS ON THE PROPOSED COMPLEX TERRAIN DISPERSION MODELING PROGRAM

BY

DR. ROBERT G. LAMB

1. INTRODUCTION

Regardless of whether one is concerned with flat or complex terrain, the objective of air pollution modeling efforts is to develop a means of predicting the second highest concentration that will occur in any year from a source of given location and specifications. Actually, no one can say what the highest or second highest concentration will be at any site in any future year because the physical processes that control concentrations, principally the weather, are not deterministic. At best one can estimate the probability that a particular concentration will occur based on projected source emissions and historical weather data. Thus, in the discussions that follow, we will view the pollution modeling problem from the probabilistic standpoint.

One reason for doing this is to get away from the prevalent notion that understanding the dynamics of plume impaction on hills is the key to the complex terrain modeling problem. We will discuss below two other equally important aspects of the problem that must be resolved before the above stated goal of diffusion modeling can be achieved.

Another motivation is to illustrate the magnitude of the overall modeling objective. There are 8760 hours in a year so the task of estimating the second highest hourly averaged concentration in a year is essentially that of finding the value C_2 that satisfies the equation

$$\int_{C_2}^{\infty} p(C)dC == \frac{1}{8760} \qquad (1)$$

where p(C)dC is the probability that the hourly averaged concentration at the given site is in the range C to C + dC.

It is evident from this expression that the stated objective of pollution modeling is an ambitious one in that it requires a rather precise knowledge of the form of the upper tail of the concentration probability density p(C). Under the best of conditions they are limited to the accuracy with which the probabilities of the extrema of any process can be estimated. Consequently, we should devote part of any modeling effort to the question of whether, given the inherent uncertainties with which we can describe the phenomena that effect pollutant concentrations in complex terrain, we can ever achieve a model of the second highest concentration that provides estimates reliable enough to form the basis of highly costly emissions control procedures. Stated another way, we should compare the magnitude of model uncertainties, translated into dollar costs of control equipment, with the cost of alternate methods of estimating the second highest concentration, such as long-term tracer monitoring studies conducted at prospective plant sites. The results of these types of analyses might lead to the abandonment of complex terrain modeling altogether.

In any case it is desirable to determine as soon as possible (if it is determinable at all) the inherent limits on the predictability of the probabilities of concentration extrema in complex terrain. This knowledge gathered early in a multi-year model development program could guide the redesign of those studies planned for subsequent years and thereby circumvent the expenditure of large amounts of money and manpower pursuing goals that are unattainable. Thus, one criterion for the design of a long-term complex terrain modeling program should be that the information required to analyze the predictability question be gathered during the initial phase of the study.

The remaining design criteria can best be formulated by examining the information needed to solve the equation that gives the probability density p(C).

For this purpose it is convenient to collect the physical processes that affect transport and diffusion into several groups as follows:

Firstly, we isolate the geostrophic (or synoptic scale) meteorological conditions over the given site at a given time. The important variables are the wind speed and direction, temperature and dew point, all measured at the geostrophic level (say 700 mb); cloud cover; and elevation of the subsidence inversion base. We will denote this set of variables by the symbol G and refer to it often in the probabilistic analyses as the "event" G, to signify the occurrence of a specific set G of these variables.

Secondly, we isolate the micro-mesoscale meteorological conditions at the site. The important parameters here are the three-dimensional flow and temperature fields in a layer roughly 1 km deep based at the source elevation and extending over the entire horizontal region in which significant concentration levels are likely to occur. We will represent these fields by the symbol M and refer to them occasionally as the "event" M.

Thirdly, we consider the plume rise and buoyancy generated plume spread processes. The three-dimensional coordinates of the plume centerline; the plume's width, depth and material content as functions of distance along the centerline; and the frequency and lateral extent of plume meander will jointly be denoted by the symbol (and event) P.

Finally, we have the processes that govern plume impaction. We are not interested in the details of these processes themselves, but rather with the ground-level concentration they produce for given P. Thus, we define the event C as the occurrence at the given site of a particular concentration value, say C. The impaction processes are implicit in C.

The four components of the problem we have just defined are interlocked: a particular set G of geostrophic conditions occurs at the site; these acting in concert with physical properties of the local terrain give rise to a particular micro-mesometeorology M; in this flow the power plant emitting material at a given rate and temperature from a stack of given height and diameter produces a plume of specification P; boundary layer processes bring this plume into contact with the ground causing a concentration C. Thus, the task of estimating the probability that a particular concentration C will occur at some point is simply that of determining the total probability that all combinations of these four events that produce the value of C will occur.

The probability that M, say, is in the range N to N + dM is p(M)dM. Since M is dependent on G, p(M)dM is different if we are given that a particular G has occurred. We represent this conditional probability by $p(M|G)dM$. Similarly, we can define the conditional densities $P(P|M)$ and $p(C|P,M)$.

Using these functions and basic statistics theory, we find that p(C) that enters in Eq. (1) is given by

$$p(C) = \iint p(C|P,M)p(P|M) \int p(M|G)dGdPdM. \qquad (2)$$

Equations (1) and (2) are the basic form of the "second highest" concentration model that will serve as the focal point for the discussions that follow. We wish to emphasize here that (1) and (2) are not an esoteric set of equations of academic value only. Rather, they embody in highly condensed form all of the physical processes that are believed to be important in the complex terrain dispersion problem and therefore any model that is to yield reliable estimates of concentration extema probabilities is reducible to the form of (1) and (2).

In order to provide a better understanding of the physical meanings of each of the probability kernals in (2), we shall discuss each below. From these discussions will emerge a picture of many of the current needs in complex terrain modeling.

A. The Impingement Kernel, $p(C|P,M)$

Recalling the definitions of P and M, we see that $p(C|P,M)$ is essentially a relationship among the concentration at some ground-level site, say a hillside, and the height, width, depth, and material content of the plume and the ambient flow speed, direction and temperature stratification. It is precisely this relationship that has been the subject of nearly all the laboratory and field studies of complex terrain dispersion that have been conducted to date. In keeping with the established terminology, we shall call $p(C|P,M)$ the impingement kernal because it embodies only the processes that bring a given plume into contact with the ground.

Over flat terrain, which incidentally is also within the scope of applicability of (1) and (2), this kernal is frequently assumed to have the conventional Gaussian form. In this expression, P is represented by the effective source height, σ_y, σ_z and source emission rate Q; and M is represented by the wind speed $\bar{u}$ and the atmospheric stability, that establishes the magnitudes of σ_y and σ_z. In this instance, the mean flow is everywhere parallel to the ground and hence material impinges on the surface only as a result of the action of vertical velocity fluctuations, or eddies, in the turbulent boundary layer. It is the universal character of steady-state turbulence over a flat surface that is manifested in the universal Gaussian expression assumed for $p(C|P,M)$ in smooth terrain.

In complex terrain the mean flow is not everywhere parallel to the earth's surface and therefore it can act in conjunction with turbulence to transport plume material to the ground. In this case the form of $P(C|P,M)$ is influenced strongly by the size and shape of the hill, by its surface roughness, and possibly by the nature of the terrain just upstream of the hill. It is speculated that if time and length variables are non-dimensional by the proper combinations of flow variables and characteristic length scales of the hill, universal forms for the relationship $p(C|P,M)$ exist that will be applicable in complex terrain just as the Gaussion plume formula is assumed to apply over flat areas. However, if we consider in detail the physical processes that affect concentrations on the side of a hill, we see that previous laboratory studies are not adequate in themselves to establish the true form of p because they do not account for the effects of turbulent boundary layers.

No matter how large or small a hill may be and no matter how stably stratified the flow may be, there exists a turbulent boundary layer adjacent to the hill's surface. The turbulence is generated in part by the shear in the velocity field; partly by obstacles such as boulders, trees, etc. that may dot the surface; and partly by heating and cooling of the hillside. The last process is probably very important on hills the size of those that are likely to experience plume impingement. (Considering the fact that power plant stacks are typically 200-300 meters high and that plumes commonly rise 300-500 meters in stable conditions, we estimate that the characteristic hill size of interest is 500-800 meters). On the sunlit side of a hill, heating generates upslope flows that produce a convective boundary layer that increases in depth from the base to the top of the hill. Conversely, on the shadowed side and at night, surface cooling generates a downslope flow that is deepest at the base of the hill and very shallow at the hill top. On the windward side of a hill this downslope flow would accentuate the surface layer wind shear and possibly enhance turbulence levels.

Furthermore, hills several hundred meters tall usually have smaller hillocks superposed on them and ravines cut in their sides. These features generate turbulent wakes that are shed and advected along the hill's surface to further augment the depth and intensity of the turbulent boundary layer.

The essential point here is that when a plume impinges on a hillside, it must travel through this turbulent surface layer to reach the ground. In the process plume material is diluted by mixing with clean air in the boundary layer; and depending on the character of the turbulence in the surface layer, for example, the extent to which it is composed of wake turbulence, the plume material may meander across the surface of the hill and thereby produce quite low time averaged concentrations.

Figures A-1 and A-2 depict the processes we have just described. The main purpose of these figures is to illustrate that the process of dispersion within the immediate environment of the hill is practically identical to that of plume fumigation from a stable layer aloft.

They also illustrate that concentrations at the surface of the hill are dependent upon the depth of the hill's boundary layer (HBL) at the point of plume entry, the intensity and scale of turbulence in the HBL, the mean flow speed in the HBL, and the rate at which plume material is fed into the HBL from the laminar layer above. The latter is dependent upon the angle that streamlines in the laminar region make with the top of the boundary layer. Since laboratory simulations have purposely suppressed boundary layer formation by using very smooth hills and approach planes (they have also ignored thermal boundary layer effects), it would seem that those studies cannot produce meaningful expressions for hill surface concentration values. However, they should be able to yield quantitative information on the manner in which hills distort the mean steamline patterns in the laminar flow regions around them. Even this information must be used with caution until it is demonstrated that the turbulent boundary layer does not significantly alter the flow in the laminar region.

In summary, we have argued that to obtain the functional form of the impingement kernel p(C|P,M) under stable conditions in complex terrain, we require both a quantitative description of the mean steamline patterns in the laminar flow regions around hills and certain characteristic features of the surface turbulent boundary layer. The specific quantities required are (1) the depth of the boundary layer as a function of distance along the hill, (2) the intensity and scale of the turbulence and the mean flow speed in the boundary layer as functions of location, and (3) the rate at which fluid from the laminar region enters the boundary layer at each point. As we stated earlier, the last quantity is dependent upon the angle that steamlines in the laminar region make with the outer surface of the boundary layer. This is information that laboratory and specially designed field studies can provide.

Such studies can also provide the boundary layer information outlined above and with it the diffusion experiments necessary to relate that information to the rate of dilution of plumes that enter the boundary layer and impact the ground. As we noted earlier, this dilution process is fumigation-like in nature. Having all this information as a function of M, the physical characteristics of the hill (including its surface roughness and that of immediate upstream areas), and cloud cover and albedo from which we can estimate surface

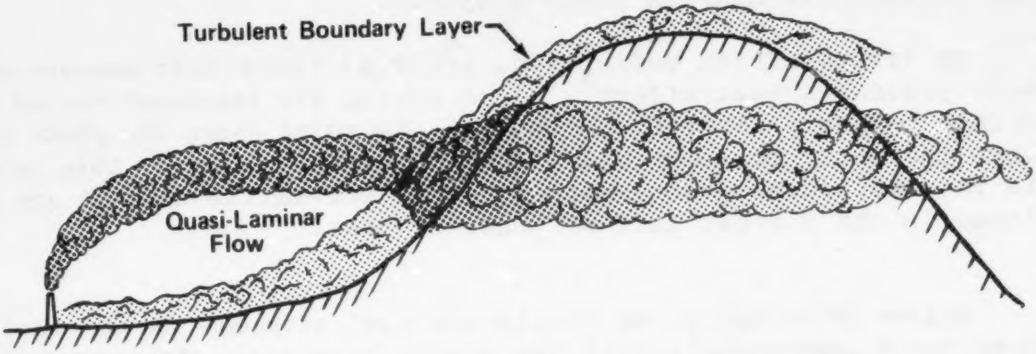

Turbulent Boundary Layer
Quasi-Laminar Flow

Figure A-1. Diagram showing flow pattern of stack plume - nighttime.

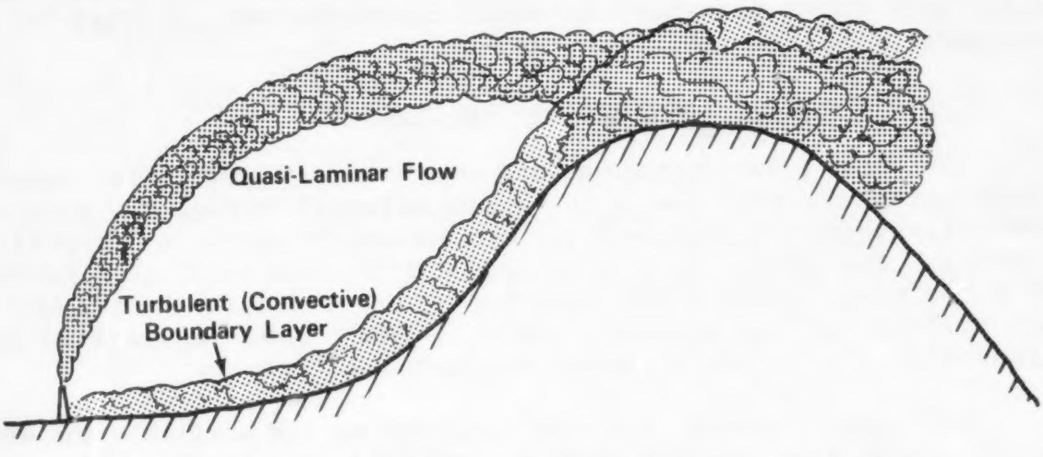

Quasi-Laminar Flow
Turbulent (Convective) Boundary Layer

Figure A-2. Diagram showing flow pattern of stack plume-daytime.

heat flux, we can formulate the kernel $p(C|P,M)$ required to predict the desired concentration probabilities. Later we outline field studies that can address these subjects.

By virtue of its definition, $p(C|P,M)$ takes into account only those processes that affect a plume during its transport across the surface boundary layer to the ground. The point where the plume contacts the outer boundary layer, the plume's dimensions at this point, its rate and envelope of meander, etc., are variables that are included in the P event that we consider next.

Before proceeding, we should add that although the discussions above dealt exclusively with the stable flow case, the same sets of information are required for neutral and unstable flows as well. It has been observed in the Geysers area of California, for example, that maximum ground-level concentration occurs under stagnant, convective conditions. This situation may be typical of sources in long, deep and relatively narrow canyons or valleys where all of the stably stratified flows transport material approximately parallel to the contours of high relief features.

B. The Plume Rise/Transport Kernel, $p(P|M)$

The event P was defined as the occurrence of a specific, detailed plume structure from the point where material leaves the source to the point where it just enters the boundary layer of a terrain feature. The probability density $p(P|M)$ of this event is a function of M and also of the stack height and diameter, and the temperature and velocity of the exhaust. Thus, loosely speaking, $p(P|M)$ is a plume rise and transport model for complex terrain.

Over flat regions, empirical expressions are available for estimating plume rise under stable and neutral conditions. Under these conditions, it is assumed that once a plume reaches its equilibrium level, it follows a straight path indefinitely far downwind from the source. Neither this assumption nor the flat terrain plume rise formulas are applicable a priori to complex terrain. One reason is that low-level stable flows in complex terrain are not generally horizontally homogeneous like they are over uniformly flat ground, and thus plumes are often observed to wind along irregular paths and to meander horizontally. Furthermore, in rough terrain regions, vertical profiles of wind and temperature often exhibit extreme variations with height. The extent to which these variations affect plume rise and spread is not known, but it must be established in order to obtain reliable estimates of $p(P|M)$. In addition, the magnitude and frequency of plume meander must also be determined and related to M and characteristics of the topography. For example, the meander phenomenon may be due to vortex shedding behind large hills or it may be caused by "sloshing" of cold air in a valley under the influence of the wind stress exerted by the geostrophic flow aloft. In these cases it might be possible to establish at least bounds on the meander magnitude and frequency based on hill size, flow speed, valley width, geostrophic wind speed, etc.

We will suggest field measurements to investigate these phenomena later.

C. The Micro-Mesoscale Meteorology Kernel, $p(M|G)$

It has long been known that the differential heating and cooling of the sloping surfaces in complex terrain generates local circulation regimes much like the differential heating and cooling of adjacent land and water surfaces gives rise to lake and sea breeze circulations. It is the three-dimensional structure (speed, direction and lapse rate) of these local flows that is embodied in our definition of M.

One of the problems that complicates the modeling of dispersion in complex terrain is that M does not normally exhibit the horizontal uniformity that it does over flat areas well inland from large bodies of water. In other words, over smooth, inland sites the smallest horizontal spatial variations that exist in flows have length scales of several tens of kilometers; whereas, in complex terrain the corresponding scales can be an order of magnitude or more smaller. Thus, over flat, inland terrain meteorological data from a rather coarse network of stations are adequate to piece together a reasonable three-dimensional description of the flow, i.e., M; and if sufficient quantities of historical data are available, the probability density $p(M)$ can be estimated.

By definition

$$p(M) = \int p(M|G)p(G)dG, \qquad \text{cf Eq. (2)} \qquad (3)$$

In complex terrain the density of meteorological stations is generally much to small to determine M. However, there is sufficient information to obtain G and $p(G)$. This suggests that there are two avenues of approach to the gathering of data needed to determine $p(M)$.

One is to undertake an extensive study of the physical processes that govern micro-mesoscale flows in complex terrain with the objective of developing a model of $p(M|G)$ applicable to all types of terrain. The processes involved are almost totally dominated by the terrain features, which incidentally have been documented by the U.S.G.S. with extreme resolution for the entire country. This study would involve field projects, physical modeling in the laboratory, and numerical simulations. At this juncture, there is evidence that a usable model of $p(M|G)$ cannot be developed.

The second approach to gathering the requisite data is to deploy at every proposed site of a power plant a network of meteorological stations dense enough to resolve M, and to collect data for a long enough period (at least two years), to determine p(M). This approach would be expensive and time-consuming, and unless the measurement network were designed properly, the information gathered might not be useful at any other locations. One might argue that if this type of an approach were taken, it would make more sense to bypass the meteorological measurement altogether and to perform the tracer studies necessary to determine p(C) itself. For example, one could erect a tall tower, at least as tall as the lowest anticipated plume elevations, and release a different inert tracer steadily from various levels of the tower. Automatic syringe samplers deployed over the surrounding area and collecting hourly air samples on a continuous basis would provide the information required to determine p(C) directly. No aircraft observations or mobile measurements of any sort would be necessary. The obvious advantage of this method is that it circumvents the uncertainties that attend model calculations and thus it provides a much more reliable basis for making control decisions.

The preliminary design, planning, site selection, etc., necessary for large power plants require several years to perform. Thus, if a monitoring study such as this one were begun at, say, the three most preferred sites, by the time plant construction was ready to begin, adequate concentration data would have been gathered to determine the degree of emissions controls required. One problem with this method is that a plume of passive tracer material does not expand as much under stable conditions as that of power plant emissions because it lacks the buoyancy. For this reason, measurements of wind and temperature on the tracer release tower would be needed to estimate the degree to whch buoyancy would enhance dispersion.

The purpose of this digression was to point out that there are alternatives to modeling dispersion in complex terrain. We believe that a critical evaluation of these various methods should be conducted as a part of the proposed modeling program, weighing the uncertainties that attend model predictions, translated into dollar cost of control equipment, against the cost of monitoring studies where uncertainties are greatly reduced. Results of predictability studies like those suggested earlier in this report would be of value in this task.

Returning to the discussion of M and p(M), we can view M as the resultant of a local, thermally induced circulation superposed on a terrain augmented geostrophic flow. In instances where the geostrophic flow is weak, the local circulation will dominate, and hence M will reflect the characteristics of the local terrain. Since these features are constant, we would expect that for this set of "weak" geostrophic flows and given cloud cover conditions and hour and day of year, there is negligible variation within the corresponding set of M. It is likely that in many areas the highest ground-level concentrations occur during the "weak G" situations. Where this is the case, being able to describe the local circulation regime and knowing the probability of "weak G" are all that are required with regard to p(M) to solve (2).

Another simple case is that where the local circulation is so shallow that plumes are able to break out of it and enter the geostrophic flow above. In this case we replace p(M) in (2) with p(G) (see also Equation (3)) and M in $p(C|P,M)$ with G. Recall that p(G) is usually known.

In situations where plumes are frequently confined to the local flow; i.e., the layer described by M, and neither the terrain nor the geostrophic flow dominate M, the modeling problem is much more complicated. It is this class of problems in which the highest modeling uncertainties will exist.

2. SUGGESTED FIELD EXPERIMENTS

We have shown that there are three basic components of the complex terrain modeling problem and have emphasized that all three must be understood to meet current modeling objectives. One of these components, namely the impingement processes, has already received a great deal of attention. The other two have not.

We have also emphasized the uncertainties in model calculations, especially in complex terrain environments, and have stressed the need for studies aimed at assessing quantitatively the inherent limits on the predictability of concentration extrema in such areas. The results of this study should be used to perform cost/benefit calculations to determine whether there are possibly methods other than modeling that can best meet existing regulatory needs.

A. Studies Relevant to the Impingement Kernel, $p(C|P,M)$

The major information required to formulate $p(C|P,M)$ is the following:

1. A characterization of the three-dimensional streamline patterns in the laminar flow region around hills during stable conditions, expressed in terms of Froude number, hill height and aspect ratio, surface roughness, surface heat flux, etc.
2. Depth of the boundary layer adjacent to hills as a function of distance along the hill, expressed in terms of mean flow speed and stability in the laminar region, surface roughness and heat flux.
3. The intensity and scale of turbulence in the boundary layer as a function of distance along the hill, expressed in terms of the same parameters as (2).
4. Mean flow speed in the boundary layer and fluid transport rate into the boundary layer from the laminar region, both expressed as in (2).
5. A mathematical relationship among the parameters listed in (2) - (4) above and the rate of dilution of material as it moves across the boundary layer from the laminar region to the ground.
6. The range of variation in the dilution rate parameter (see (5)) and the laminar region streamline patterns (see (1)) resulting from upstream random arrays of hills and depressions of heights and depths less than that of the study hill under various conditions of stability, heat flux, etc. (This information is needed in the predictability studies, to formulate an estimate of the magnitude of uncertainty in model calculations.) These bounds would be expressed in terms, say, of rms height of upstream terrain, Froude number of study hill, etc.

There have already been a number of laboratory studies conducted to investigate (1). However, the applicability of those results to complex terain is questionable because the Reynolds numbers achievable in the laboratory are many orders of magnitude smaller than those characteristic of rough terrain. Also, previous laboratory simulations have not included upstream turbulent boundary layers or non-zero heat fluxes.

Below we outline an experiment that can address all six of the subject areas listed above and, in addition, provide virtually a conclusive answer to whether the results of the laboratory studies mentioned are applicable to the atmosphere.

The basic experimental design involves a simulated hill constructed of flexible material such an canvas, mylar, or other suitable material stretched over metal hoops or rods to achieve particular shapes. The hill is hung from a cable stretched between two towers and, being flexible, it can be raised or lowered to any height desired (see Figure A-3). The hill would be erected on a dry lake bed; e.g., Lake Bonneville, where the ground surface is very flat for many kilometers around and stably stratified winds are frequent.

Tracer material would be released from desired elevations and distances upwind of the hill and sampled on the hill's surface by instruments accessible through ports in the fabric that composes the hill. All monitoring and recording of concentrations and flow parameters would be performed at a central facility located inside the hill that is connected to all instruments by cables.

The boundary layer of the flow approaching the hill would be controlled by raising fences of fabric panels as shown in Figure A-3. These "roughness" elements could be replaced by or used together with arrays of small hills, perhaps inflatable structures, to study dispersion on a hill surrounded by very rough terrain in its immediate vicinity.

Positive and negative heat fluxes could be achieved on the hill using perhaps fine water sprays on the exterior surface and gas space heaters exhausting into fabric ducts on the inside hill surface.

Instruments to measure concentration and flow variables in the hill's boundary layer could be attached to poles 2-3 meters long and placed in position from ground-level inside the hill as the hill is raised in place. These poles would be secured to the metal framework that supports the fabric.

Some of the advantages of this experimental design over others; e.g., instrumenting a real hill, are:

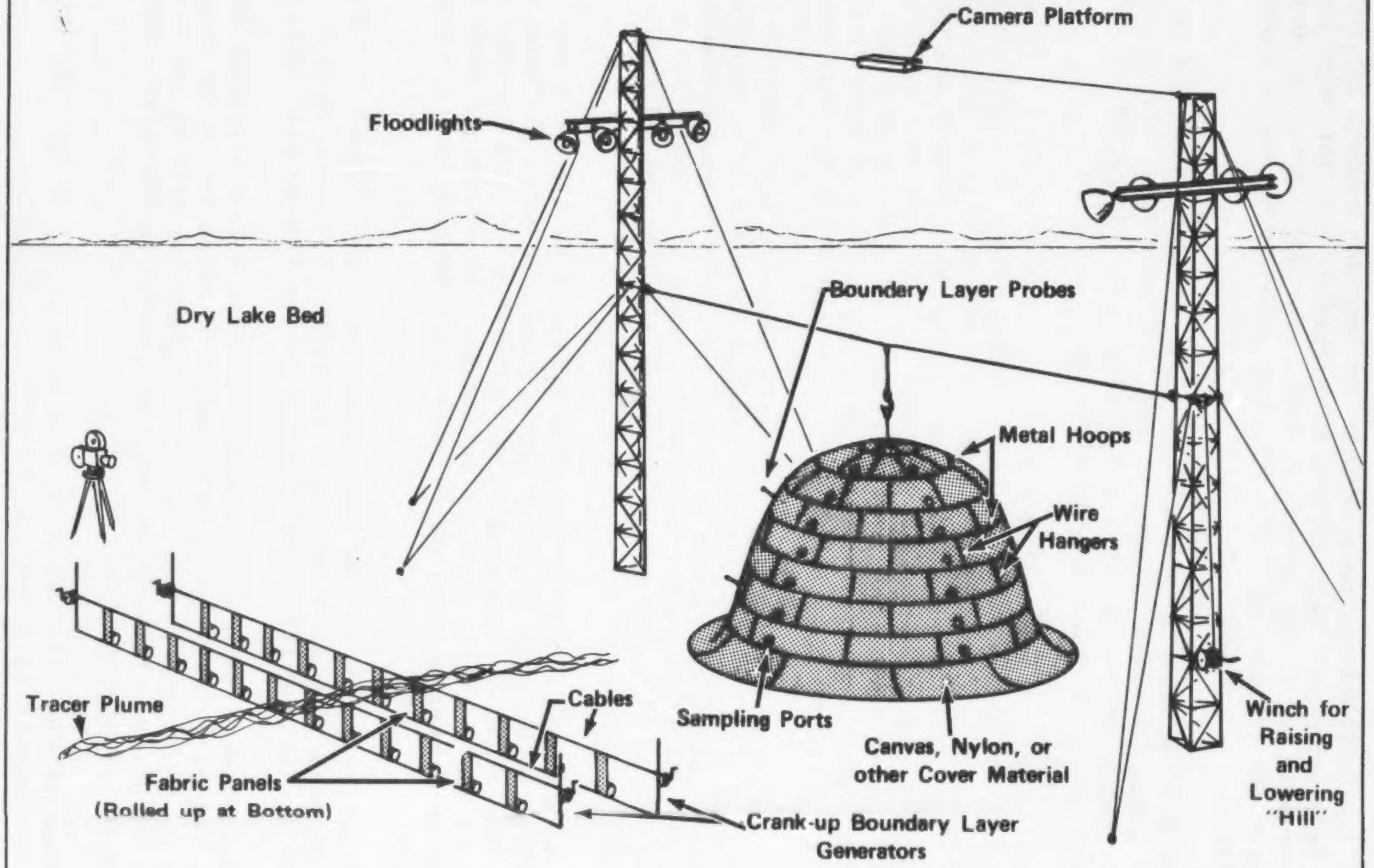

Camera Platform
Floodlights
Dry Lake Bed
Boundary Layer Probes
Metal Hoops
Wire Hangers
Tracer Plume
Cables
Sampling Ports
Canvas, Nylon, or other Cover Material
Winch for Raising and Lowering "Hill"
Fabric Panels (Rolled up at Bottom)
Crank-up Boundary Layer Generators

Figure A-3. Experiment for determining p(C|P,M). The data monitoring and recording center is located inside the hill. All probes are connected to it by cable. Samplers and probes are installed from ground-level from within as the hill is raised.

1) It provides a laboratory with complete control over hill size, shape, roughness and heat flux. For example, the hill height could be changed gradually during a single experiment to examine Froude number effects. Equally important is the control possible over the characteristics of the turbulent boundary layer of the approach flow. None of the parameters just tested is controllable with a real hill.

2) Wide scope of experiments. All six of the subject areas that require study to formulate the impingement kernel can be investigated.

3) Having the monitoring center located inside the hill minimizes the logistics problems of servicing the instruments and relaying data to the monitoring site (e.g., cable rather that radio data transmission is used). The flat terrain site and the support towers that suspend the hill facilitate measurements of the approach flow and filming operations.

The maximum hill sizes and flow speeds used in the EPA Fluid Modeling Studies are 25 cm and 50 cm sec^{-1}, respectively. The fluid used in water, $\nu \simeq .01$ cm^2 sec^{-1}. The hill size envisaged in the present experiment is 25 meters (larger ones are possible) and flow speeds of 4 m sec^{-1} are possible. Thus, Reynolds numbers 100 times larger than those achieved thus far in laboratory studies could be obtained. Favorable comparisons of results obtained over this range of Reynolds number would provide strong justification for continuing and expanding laboratory simulations.

The experiment just described is restricted to studies of stably stratified flows. Modeling dispersion under free convective conditions may be possible using numerical models currently in development. To apply those models to complex terrain, we require at least the following information:

1) Probability density of vertical and horizontal velocity fluctuations over heated hill surfaces of various heights and widths and the same information over shadowed surfaces.

2) Horizontal scale and characteristic vertical velocity of thermals as a function of underlying hill and ravine sizes.

3) The parameters listed in 1 and 2 as functions of sun angle, cloud cover, albedo, and surface slope and height of hills.

These three sets of information could be gathered from aircraft measurements of the 3-D velocity components taken at various altitudes above complex terrain. The instantaneous data samples would have to be correlated quite precisely with the horizontal position of the aircraft so that the velocities could be analyzed as a function of the terrain features.

The case of forced convection; i.e., strong surface heat flux together with moderate horizontal winds, might possibly be modeled numerically, but there are no studies of this sort in progress now. The theoretical problems to be surmounted in developing such a model are significant, and we must conclude that large uncertainties in concentration predictions under these conditions will always exist.

B. Studies Relevant to the Plume Rise and Transport Kernal, $p(P|M)$

The major information requirements are:

1. The effects of vertical variations in wind speed and direction, temperature stratification, and turbulence energy on the plume entrainment rates of heat and mass.

2. The effects of these same parameters on plume meander; i.e., spatial oscillations in the plume centerline.

The first studies conducted should be an exhaustive analysis of the ability of current plume rise models to predict accurately plume heights, widths, and thickness as functions of travel time in complex terrain. Adequate data for this purpose exist in the Mohave, Navajo and Four Corners data sets. These studies should correlate model performance with the stack height and diameter buoyancy flux, etc.; and the characteristics of the flow, such as wind shear magnitudes, vertical variation in Richardson number, etc.

This study would expose the weak points in current models. For example, the current methods of parameterizing entrainment may not be adequate. Subsequent field studies using lidar probes of the plumes that models simulate most poorly could gather the data necessary to refine the rise and spread models. The error levels still present in refined models would be used in the predictability studies.

C. Studies Relevant to the Micro-Mesometeorology Kernel $p(M|G)$

To formulate this function requires a fundamental knowledge of the processes that govern the three-dimensional structure of flows within the first kilometer over valleys in complex terrain. There are two complementary approaches to formulating p(M|G). One is physical and numerical modeling of the physical processes involved. The second is an empirical approach based on extensive measurements of key variables in complex terrain sites of various types. The latter approach is necessary in any event because only it can supply the data required to validate numerical and physical models. An empirical model developed from field data would be used primarily to estimate the frequency, given the climatology of the local geostrophic flow G, with which a plume from a given plant might impact a particular terrain feature; and the type of vertical wind shear and temperature stratification profiles, necessary for performing the plume rise and spread estimates (i.e., P), that would occur in these cases.

We recommend that physical and numerical flow models be developed in the event that empirical formulations prove to be unacceptable.

Some of the questions that a field program should attempt to answer are:

1) How deep are valley drainage flows and how does the depth vary during the night? Can the depth be correlated with the depth of the valley, distance down the valley, etc.?

2) Are the speed and direction of drainage flows at any level functions of the slopes of surrounding terrain features of a particular scale?

3) Is the temperature stratification within the drainage flows strongly dependent on terrain features, or it is roughly the the same from one site to another and one hour to another?

4) How strong must the geostrophic flow be at a particular site to eradicate the drainage flow regime?

5) During weak geostrophic flows, does the same drainage circulation regime occur at a given site (given the same time of year, cloud cover, snow cover, etc.)?

6) Is there evidence that wind stress on the top of the cold drainage flow produces a sloshing phenomenon that could cause plume meander, and if so, is the sloshing frequency relatable to geostrophic flow speed, valley dimensions, etc.?

7) Are the radiation inversions and vertical wind speed profiles that occur over high mesas that contain deep gorges similar to those found over uniformly flat terrain?

8) To what horizontal distance from the base of an isolated ridge does the drainage flow penetrate? How does the depth vary along the ridge face?

To answer these questions and to gather the data required for model validation, we recommend the following experimental approach.

1) Locate a geographical area that contains terrain features of various types within an area small enough for the geostrophic conditions G to be assumed constant at any instant. For example, valleys of various widths, depths and lengths; mesas with river gorges; isolated ridges; etc. (One such area exists near Prescott, Arizona.)

2) Within the various terrain types deploy a network of instruments to measure vertical profiles of wind speed and direction and temperature up to about 300 m AGL continuously through nighttime hours.

3) Release and track groups of tetroons at various levels within and above the drainage flows (these data are necessary to check the accuracy of particle trajectory predictions based on fixed site wind observations).

4) Monitor meteorological variables on high terrain, make radiosonde measurements, acoustic sounder probes, etc.

The experimental setup is shown in Figure A-4. Gathering the vertical temperature and wind data continuously at numerous sites would be very costly using conventional methods. In the insert of Figure A-4, we have sketched a system that utilizes a captive balloon to gather these data at unmanned sites. The concept of the design is based on existing technology, but as far as is known, such a system does not now exist. We recommend that some portion of the modeling effort be devoted to developing low cost means of gathering the data required.

3. OUTLINE OF PROPOSED MULTI-YEAR PROGRAM

The suggested work is divided into two programs operated in parallel: One develops the required model and the other monitors the model development progress and steers the overall effort.

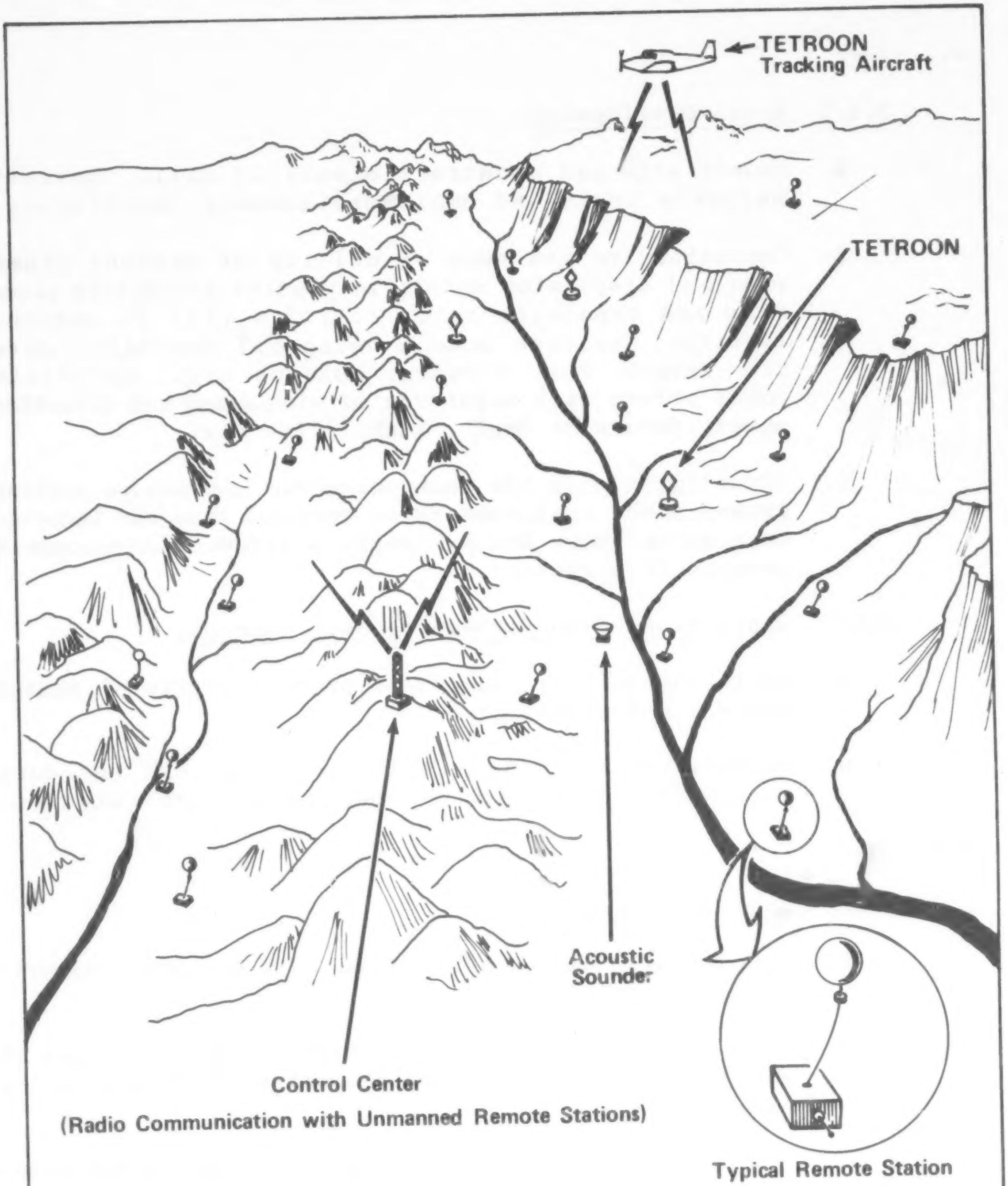

TETROON
Tracking Aircraft
TETROON
Acoustic Sounder
Control Center
(Radio Communication with Unmanned Remote Stations)
Typical Remote Station

Figure A-4. Experimental design for studying the micro-mesometeorology of complex terrain.

3.1 Year 1

3.1.1 Model Development.

A. Select site and construct simulated hill. Perform hardware tests and begin preliminary experiments.

B. Comprehensive analyses of ability of current plume rise and dispersion models to predict accurately plume rise and expansion rates ($\sigma_y(t), \sigma_z(t)$) in complex terrain. Exercise models using all available data from Navajo, Four Corners, Mohave, etc. Correlate model errors with magnitude of wind speed and direction shear, inversion depth, stabililty, etc.

C. Investigate possible techniques for inexpensive routine ground-based measurements of vertical wind and temperature up to about 300 m. Begin instrument development program if necessary.

3.1.2 Monitoring of Model Development Progress.

A. Begin theoretical studies of predictability of second highest concentration.

B. Investigate alternatives to modeling that can meet regulatory needs, such as long-term tracer studies.

3.2 Year 2

3.2.1 Model Development.

A. Full scale operation of simulated hill facility. Experiments to include:

(1) Flow patterns around hills of various shapes at various Froude numbers for comparison with laboratory simulations,

(2) Develop empirical relations between plume dilution rate and turbulent boundary layer characteristics,

(3) Establish the range of dilution rates caused by random distributions of upstream terrain irregularities.

B. Based on outcome of plume rise studies conducted during first year, perform lidar probes of power plant plumes at sites and under met conditions where plume rise and spread models were found to perform worst. Measure entrainment constants, energy dissipation rates and other parameters needed to refine the model.

C. Field test instruments for vertical wind and temperature measurements. Begin analyses of existing complex terrain data looking for influence of surrounding terrain on depth of surface inversion and flow speed and direction profiles at night; threshold of geostropic flow for micro-meso regime breakdown, etc.

D. Begin development of physical and numerical models of flow in complex terrain sites to be studied in the field next year.

3.2.2 Model Development Progress.

A. Formulate impingement kernel for cases studied to date and test against Mohave, Navajo, Four Corners, etc., data.

B. Compare refined plume rise-spread model predictions with existing complex terrain data.

C. Using results of tasks A and B above and first year predictability study, estimate modeling error assuming perfect meteorological data, i.e., perfect p(M). The outcome will be:

- Modeling objectives are achievable if p(M) can be determined with accuracy E. (This will lead to the procedure in Year 2, Model Development, Section D).

- Modeling objectives unattainable even if p(M) is known precisely.

1. Examine cost-effectiveness of alternatives to modeling investigated last year, such as long-term tracer study. If viable method found, abandon major modeling effort.

2. Reformulate air quality standards to achieve predictability -- resume model development at Task D of Year 2.

3.3 Year 3

A. Continue studies at simulated hill experimental center. Examine heat flux effects on flow patterns and boundary layer turbulence.

B. Final refinements of plume rise and spread model, culminate in final form of $p(P|M)$.

C. Begin full scale study of micro-mesometeorology at sites chosen previous year.

D. Begin validation and refinement operations on physical and numerical flow models using results from field study of Step C.

E. Begin aircraft studies of free convection for use in formulating $p(C|P,M)$ for unstable conditions.

3.4 Year 4

3.4.1 Model Development.

A. Concluding impingement studies at simulated hill site culminating in final form of $p(C|P),M)$ for stable cases.

B. Develop empirical formula for $p(M|G)$ using field data.

C. Formulate expression for $p(M|G)$ from refined physical and numerical models.

D. Continue developments of $p(C|P,M)$ expression for free convective case. Begin numerical model study for forced convective case.

3.4.2 Model Development Progress.

A. Test these expressions for $p(M|G)$ against data from Mohave, Navajo, Four Corners, etc. The outcome will be:

- p(M) can be specified with required accuracy E, in which case, continued model development.

- p(M) cannot be specified with accuracy E using model only, in which case:

  1. Prepare guideline for performing necessary meteorological measurements at any proposed plant site, i.e., measurements needed to determine p(M). Resume model development.

  2. Investigate alternatives to modeling, such as long-term tracer studies -- if viable method, abandon modeling effort.

  3. Reformulate standards -- resume model development.

3.5 Year 5

A. Amalgamate all studies into final form of model of second highest concentration and specifications for input data requirements.

APPENDIX B

PREWORKSHOP MATERIAL PREPARED BY NAWC

On June 13, 1979, NAWC forwarded a Workshop package to all the participants with information pertinent to the tasks facing each panel. Of particular concern was the need for the panels to quickly focus upon the critical issues and to facilitate the flow of information between the panels in order to achieve the goals of the Workshop. The information package included the "strawman" document by Holzworth and Snyder (Appendix A); publications by Barr, et al., (1977) from the Albuquerque Workshop on Complex Terrain Dispersion, by Argonne National Laboratory (1977) from the Chicago Specialist Conference on EPA Modeling Guideline; and by Hanna, et al., (1977) from the Boston Workshop on Stability Classification and Dispersion Parameters.

In addition, NAWC prepared material for distribution to the panel leaders on June 28, 1979, which is presented below. Subsequently, each panel leader contacted their respective panel members with both written and oral instructions prior to the start of the Workshop in Raleigh.

INFORMATION FOR EPA WORKSHOP PANEL LEADERS

PREPARED BY NAWC

1. CONCEPT OF PANEL'S ROLE

1.1 Model Evaluation and Application/Model Development and Analysis Panels

These panels must generate the basic approach of the Workshop as a whole during the first session (Tuesday AM). They must review and select from the basic scenarios which approach EPA should follow in their overall program.

Specifically, the goals of modeling must be considered and established and the relative importance must be given on such topics as:

- Centerline plume impaction
- Maximum concentration value
- Type of models to be considered and their relative merits
- Measurement needs
- Scale of experiments - Simple controlled (Snyder) versus full-scale power plant studies
- Required resolution
- Priority of various parameters
- Physical modeling
- Plume rise/initial dilution

Furthermore, the Model Evaluation and Application Panel must address such topics as peak/mean ground-level impacts and locations of impacts; i.e., the overall goal of a model development program relative to the users.

1.2 Experimental Design Panel

Initially this panel should discuss in general the ramification of carrying out simple, controlled tracer experiments versus large scale power plant experiments. They must address the relative programs and budgetary requirements and provide interaction with the Measurement Techniques Panel on what is required to carry out different programs.

Once the scale, resolution, and emphasis of the experiment have been decided, discuss:

- Type of tracer and gas measurements
- Ambient measurements
- Potential locations
- Logistics and costs
- Surface measurements and instrumentation
- Aircraft instrumentation
- Tracer samples
- Physical modeling techniques

1.3 Measurement Techniques Panel

Again, this panel will have to start off with general assessments of measurement requirements for different types of field programs. Of particular concern is the area of turbulence versus meteorological parameter measurements. A lack of knowledge of relative rates of diffusion for different elevations and stability, as well as different terrain, has resulted in difficulties with model verification.

Once the experiment design parameters have evolved, discuss methods of data acquisition and recording. Discuss accuracies and calibration techniques for meteorological measurements, gas analyzers, and tracer analyzers. Discuss the applicability of various types of techniques and potential for using newly developed remote sensing devices for augmenting experiment usefulness.

Discuss practicality and costs. Interact with

- Data Management - Discuss data reporting formats, data control, instrument accuracies.

1.4 Data Management and Quality Assurance Panel

Before this panel receives clear indications of the basic goals and concepts which the Modeling Panels will zero in on, this panel should address such questions as how to utilize the wealth of data collection in the past by government, utility industry, and private firms.

- Discuss potential methods of collecting and utilizing data from past tracer and measurement programs
- Discuss quality assurance methods in view of experiment emphasis
- Discuss methods of data management which allow easy display and correction
- Consider costs, material requirements

Interaction

1) Discuss best data formats for data from past and future experiments with model application and evaluation panel.

2) Discuss reporting methods with measurement techniques and experiment design panels.

2. INTERACTION OF PANELS

Guidance provided by George Holzworth, the EPA Project Officer for the Workshop, suggests that both source-oriented (as per example in Holzworth's "strawman"), and receptor-oriented (as per example in Snyder's "strawman"), can be accomodated in the long-term EPA research plans. However, specific experiment design, scheduling, priority of research, and interaction with other programs (i.e., EPRI, DOE, and NOAA) are major considerations for the Workshop.

The present Workshop plan calls for alternate panel and plenary sessions arranged so that after an initial plenary session on Monday, there are at least three separate feedback loops between individual and assembled panels on the succeeding days: Tuesday through Thursday. Separate panel leaders meetings are part of the loops, with their closing session on Friday. Figure B-1 diagrams the information flow in each loop. Arrows pointing both ways indicate flow between panels at plenary sessions. The single direction arrows, on the other hand, are meant to emphasize the natural flow of developing ideas from panel to panel. The MD&A Panel heads the column because it has to be the original source of a well-defined quantitative demand on the other panels for development and critiquing of the MD&A panel's particular idea. It seems natural for MD&A to ask ED how they would test the idea in an experiment; then ED asks MT about possible measurements techniques, and MT passes the idea in its current stage of development to DM & QA to acquire their input on how the data can be managed. Finally, ME&A plays some conceptual simulations to see whether the particular idea, at this stage, will fly, and if so, whether it meets their set of applicability criteria. In succeeding loops the particular idea is either refined or discarded. Finally, on Friday, the panel leaders polish a draft report covering the surviving ideas and fit them together as a consistent set of program recommendations.

Probably not all ideas finally developed will appear in the first loop, but may be appended as inspiration produces them along the way. The inspiration for a new idea may come from any panel and should be inserted into the pipeline at the first available plenary session. At the initial plenary session on Monday many ideas will be formulated and these will serve as the initial "seedbed". Some ideas not meeting wholehearted support at this session could still be subject to processing at least once through the loop to make sure everyone has a chance to think the matter through.

A more specific example of how the Panels will interrelate is shown in Figure B-2, which is a flow chart showing how some specific recommendations would evolve. This would begin with listing of the general objectives and parameters to be measured by the Model Development and Model Applications Panels. Their ideas would be passed on to Experimental Design, who would devise an instrumentation array design and recommend sampling modes (time of day, time of year, duration, etc.). Their list would go to the Measurement and Data Management Panels, who would recommend specific instruments and list data handling/QA-QC, respectively. Those recommendations would go back to the other panels again, and each would refine the original design and develop a summary of recommendations.

A suggested schedule for the week is shown in Figure B-3. The specific recommendations, as shown in the flow chart, are connected

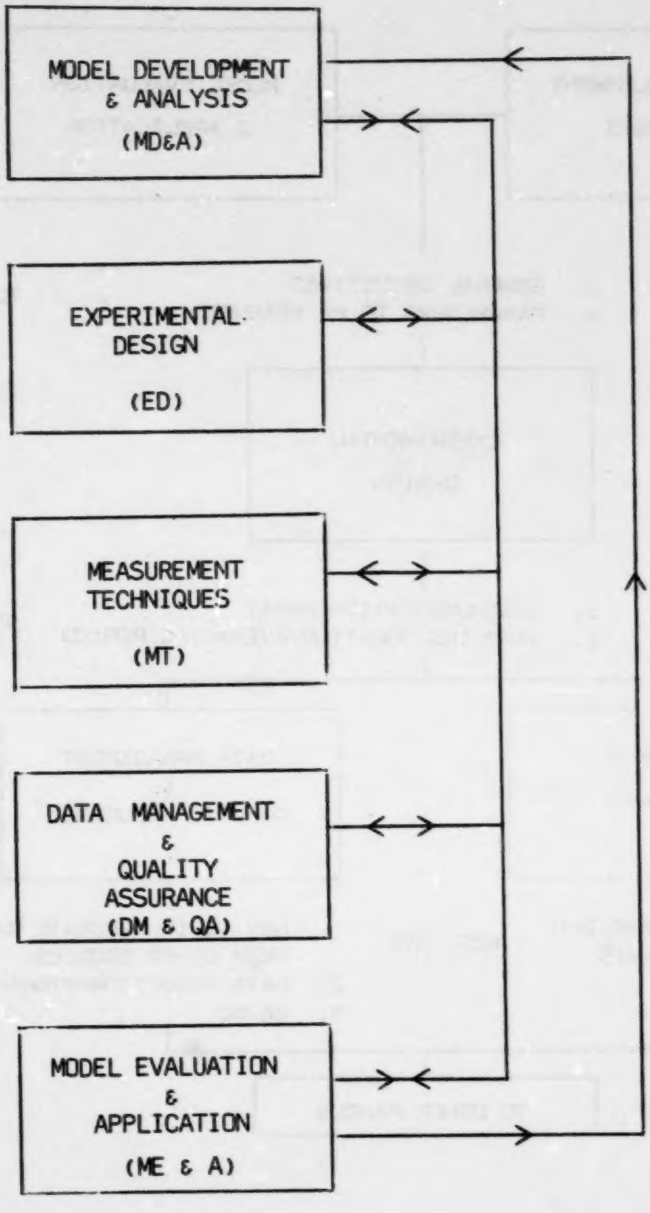

MODEL DEVELOPMENT & ANALYSIS (MD&A)
EXPERIMENTAL DESIGN (ED)
MEASUREMENT TECHNIQUES (MT)
DATA MANAGEMENT & QUALITY ASSURANCE (DM & QA)
MODEL EVALUATION & APPLICATION (ME & A)

Figure B-1. Flow diagram for Workshop.

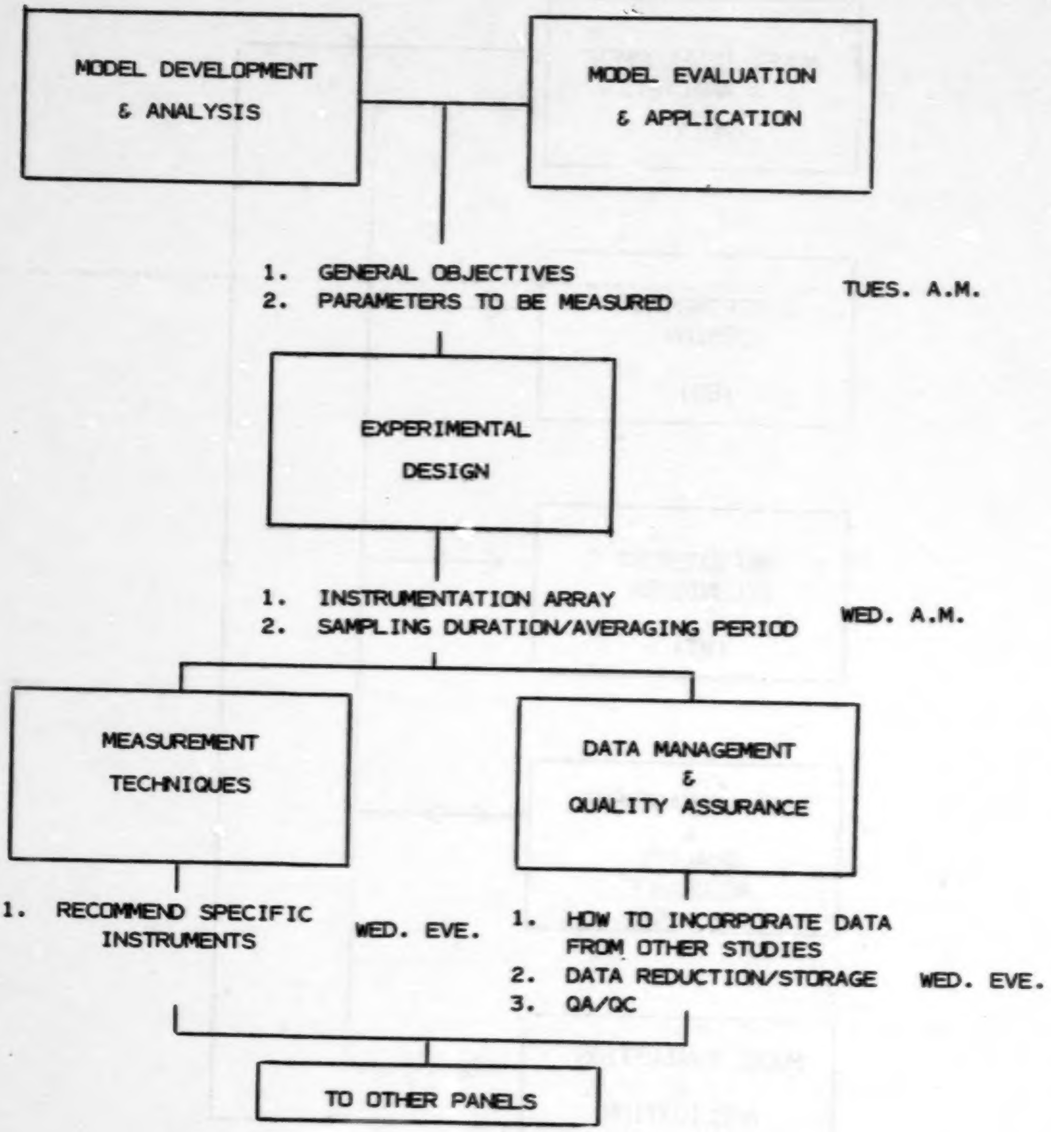
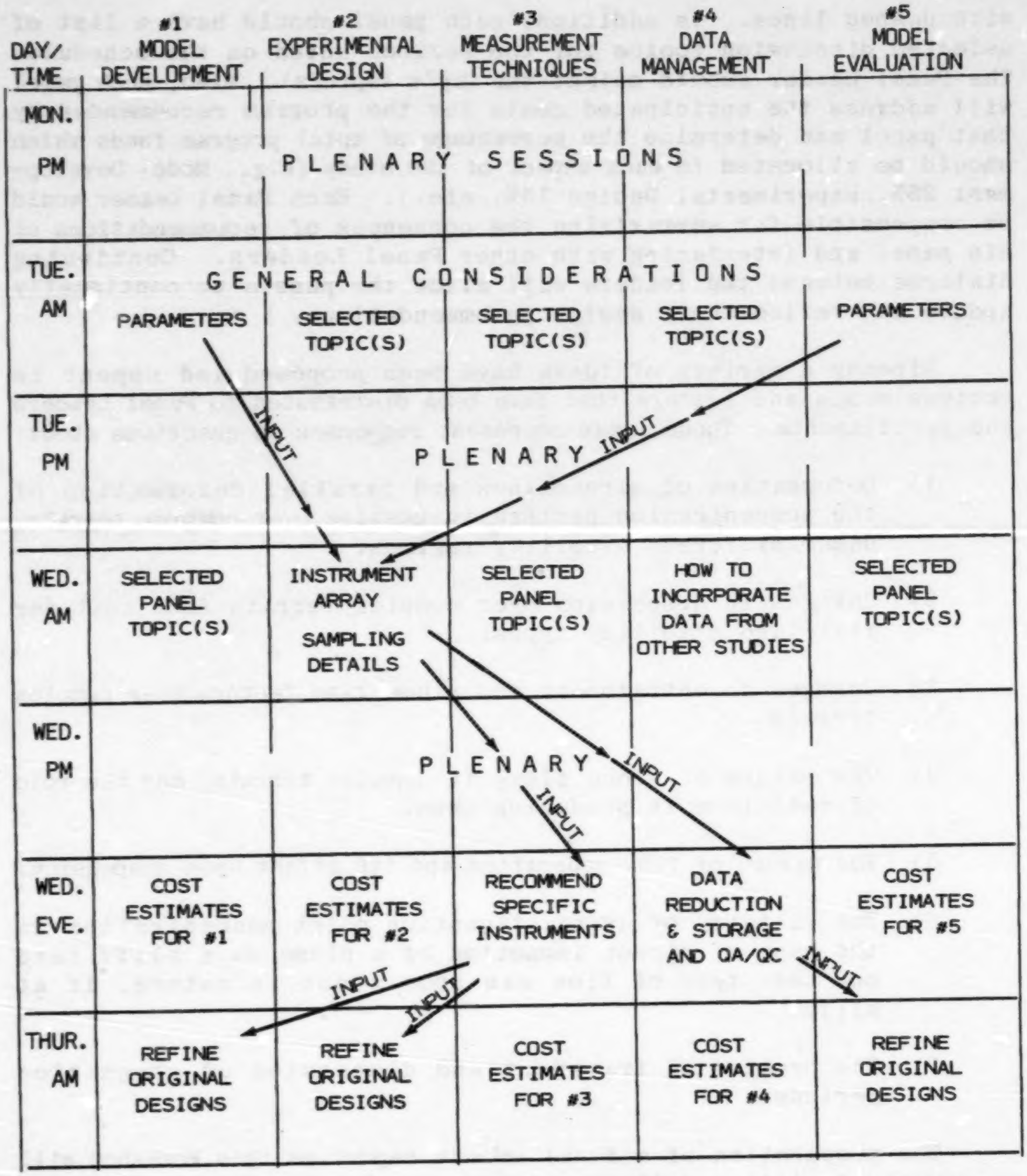

MODEL DEVELOPMENT & ANALYSIS
MODEL EVALUATION & APPLICATION
1. GENERAL OBJECTIVES
2. PARAMETERS TO BE MEASURED
TUES. A.M.
EXPERIMENTAL DESIGN
1. INSTRUMENTATION ARRAY
2. SAMPLING DURATION/AVERAGING PERIOD
WED. A.M.
MEASUREMENT TECHNIQUES
DATA MANAGEMENT & QUALITY ASSURANCE
1. RECOMMEND SPECIFIC INSTRUMENTS
WED. EVE.
1. HOW TO INCORPORATE DATA FROM OTHER STUDIES
2. DATA REDUCTION/STORAGE
3. QA/QC
WED. EVE.
TO OTHER PANELS

Figure B-2. Flow diagram for specific complex terrain model study recommendations.



DAY/ TIME	#1 MODEL DEVELOPMENT	#2 EXPERIMENTAL DESIGN	#3 MEASUREMENT TECHNIQUES	#4 DATA MANAGEMENT	#5 MODEL EVALUATION
MON. PM	PLENARY SESSIONS				
TUE. AM	GENERAL CONSIDERATIONS PARAMETERS	SELECTED TOPIC(S)	SELECTED TOPIC(S)	SELECTED TOPIC(S)	PARAMETERS
TUE. PM	PLENARY				
WED. AM	SELECTED PANEL TOPIC(S)	INSTRUMENT ARRAY SAMPLING DETAILS	SELECTED PANEL TOPIC(S)	HOW TO INCORPORATE DATA FROM OTHER STUDIES	SELECTED PANEL TOPIC(S)
WED. PM	PLENARY				
WED. EVE.	COST ESTIMATES FOR #1	COST ESTIMATES FOR #2	RECOMMEND SPECIFIC INSTRUMENTS	DATA REDUCTION & STORAGE AND QA/QC	COST ESTIMATES FOR #5
THUR. AM	REFINE ORIGINAL DESIGNS	REFINE ORIGINAL DESIGNS	COST ESTIMATES FOR #3	COST ESTIMATES FOR #4	REFINE ORIGINAL DESIGNS

Figure B-3. Suggested schedule for Workshop as detailed by Panel Leaders in their letters to Panel Members.

with dashed lines. In addition, each panel should have a list of selected discussion topics for the periods noted on the schedule. The Panel Leader should select the day's topic(s). Also, each panel will address the anticipated costs for the program recommended by that panel and determine the percentage of total program funds which should be allocated to each aspect of the study (e.g., Model Development 25%, Experimental Design 15%, etc.). Each Panel Leader would be responsible for summarizing the consensus of recommendations of his panel and interfacing with other Panel Leaders. Continuing dialogue between the leaders will allow the panels to continually update and refine their design recommendations.

Already a variety of ideas have been proposed and appear in various memos and letters that have been distributed to Panel Leaders and participants. These ideas represent responses to questions about:

1) Deformation of streamlines and parallel deformation of the concentration pattern in passing over complex terrain, under different stability regimes.

2) Changes in dispersion over complex terrain from that for flat-land stability types.

3) Changes in entrainment and plume rise factors over complex terrain.

4) The nature of slope flows in complex terrain, and the role of radiation in producing them.

5) The nature of flow separation and its effect upon dispersion.

6) The validity of using stagnation point concentration in the case of direct impaction of a plume on a cliff (and how this type of flow can come about in nature, if at all).

7) The problem of transport and dispersion of stagnation periods.

The preparation of a final smooth report on this Workshop will be greatly facilitated if there is an orderly recording of ideas and their development, including reasons for their discard, if that is the action taken. It would also be useful to name the persons in the notes responsible for initial introduction of an idea and those responsible for various seminal amplification of an idea. It is not necessary to record all the nuances of a debate, but careful recording of technical details (especially with instrumentation) would be helpful. It is easy to assume that everyone is familiar with code names and jargon. The principle on which an instrument works should be given along with its standard specifications.

It is most critical to the successful conclusion of the Workshop that there are adequate opportunities throughout the Workshop for interchange of information between the panels.

Since the Experimental Design, Measurement Techniques, and the Data Management Panels are very much dependent on the specific directions to be generated by the Modeling Panels, these directions must be conveyed early, no later than at the Tuesday Evening Executive Panel Leader Session.

APPENDIX C

POST-WORKSHOP COMMENTS BY PANEL MEMBERS

During a two-week period immediately following the Workshop, the panel members had an opportunity to review and comment on the written Panel Recommendations to EPA. Appendix C contains specific comments, received by Panel Leaders and the Project Director, which are presented for the purpose of amplifying the viewpoints by panel members which they believed required further clarification.

3 August 1979

Mr. Maynard E. Smith
Meteorological Evaluation Services, Inc.
134 Broadway
Amityville, New York 11701

Dear Maynard:

As we agreed in our telephone conversation concerning the report of our panel, I am writing you about a potential problem that was not discussed by the panel. This potential problem is the generation of turbulent wakes in the vicinity of the terrain interface during the field experiments by the hardware (masts, sampling devices, support equipment) and by certain activities within or near the sampling arrays that would significantly enhance turbulent mixing or otherwise alter the boundary layer characteristics during the stable regime. These wake effects are most likely to be significant for the small scale experiment but may be significant for the intermediate and large scale experiments as well, depending on the relative height and density of the natural roughness elements that are presented. It is clear that the potential wake effects or flow disturbances attributable to the measurement techniques, hardware and support activities should be carefully evaluated as part of the experimental design process and that these effects may limit the scale of the experiment.

Sincerely,

Harrison E. Cramer

HEC:bjs

REFLECTIONS ON THE SMALL HILL STUDY

by

William H. Snyder

As originator of the small hill study concept, I take this liberty to defend the plan. I feel that many aspects of the plan have been misunderstood, indeed, misconstrued, perhaps only because all have not had the opportunity to perceive the plan as first proposed. Numerous questions were raised at the Workshop; I will attempt below to answer the most frequent and serious ones.

1. Cost of Meteorological Towers: I have been assured by Mr. Michael Fleissner of Rohn Mfg. Co., Peoria, Ill., that the erected cost of a 152 m (500 ft) meteorological tower, complete with guys, lights and ladder, would range between $32,000 and $35,000. An upper estimate of the cost of installing anemometers is 6 man-weeks or $6000 (this estimate does not include the cost of the anemometers themselves). It is evident that substantial savings would be achieved by constructing 5 towers at essentially the same site and the same time. Hence, the cost of 5 meteorological towers is well within the constraints of the budget (~ 5%).

2. Scaling to a Large Hill: The primary goal of the small hill study was to understand the physical mechanisms involved in the impingement and/or diffusion of plumes to a hill surface. It was definitely not conceived as a study whose results would be applied ipso facto to the larger hill or "real" terrain. (From that point of view, however, it is interesting to note that often the results of fluid modeling studies conducted at scale ratios of 300:1, 1000:1, even 10,000:1, are applied to full scale situations, whereas, scaling the small hill results by factors of 2:1, 5:1, at most 10:1, appeared to be an insurmountable obstacle!). The point is that once we understand the physical mechanism involved in plume impingement/diffusion onto a sloping, three-dimensional surface, we will then have a much more clear idea of how to construct a mathematical model to handle the problem.

An example may help to clarify the point. Laboratory studies, guided by fundamental principles, have shown that, under strongly stable conditions, fluid is constrained to move in horizontal planes. A plume with an elevation lower than a nearby hill, therefore, cannot go over the top, but must, instead, travel around the sides. If the wind vector at the source is aimed precisely at the centerline of the hill, laboratory studies have shown that resulting surface concentrations will be essentially equal to what they would have been at the centerline of the plume in the absence of the hill. The laboratory studies have also shown, however, that surface concentrations are drastically reduced if the wind direction is changed only slightly. What is obviously lacking in the laboratory studies is the natural wind meander, which can only be obtained from field experiments. Once the physical mechanism, i.e., wind or plume meander factor, is understood, it will be a relatively simple matter to extend the concept to larger hills, where the standard deviation of wind direction fluctuations has been measured. The small hill study was conceived as a project wherein detailed and extensive measurements could be made on a manageable scale. The size of the hill (100 m) was chosen to be large enough to frequently be much higher than the very thin (sometimes absent) turbulent surface layer under very stable atmospheric conditions, yet small enough to eliminate the horrendous logistics problems of large scale experiments.

Plume meander is obviously not the only missing factor in laboratory or mathematical models. We also need to know the effects of anabatic and katabatic winds; how closely the plume centerline approaches the hill top as the stability is reduced from very stable through neutral; how frequently does "strong" stability occur and how is wind meander related to stability; how are the rules changed as the wind profile shape or the density profile shape vary, etc. If these kinds of questions can be answered from a small hill study--and I believe they can from a properly conducted one--we will have progressed a long way towards our goal of constructing a model suitable for use in complex terrain.

3. Real-Time Data Collection: At least two panels at the Workshop indicated that time averages, not to exceed 10 minutes in length, were essential to understand that some real-time data would be very useful, but dismissed the idea of total real-time data collection because of a perceived excessive expense. I contend that a real-time feedback system can be established that will be relatively simple, reliable, and of quite reasonable cost--even more economical than any other system when all factors are considered over the total duration of the small-hill study. There are three questions to be answered here: (1) What tracer/sampling system could be used? (2) What time resolution is necessary? (3) How much would a real-time feedback and recording system cost?

(a) Tracer/Sampling System: I propose to use ethane (C_2H_6) as the tracer and flame ionization detectors (FID's) for concentration measurements. Ethane is neutrally buoyant, sufficiently inert chemically and readily available at reasonable cost. FID's (total hydrocarbon analyzers) are well-understood, reliable, readily available, fast response (~ 1 sec), linear in the range of 0.5 to 10,000 ppm (i.e., can measure dilutions on the order of 2x10^6), and are not terribly expensive (~ $2500/unit). They produce an analog output voltage that is readily digitized. Adequate surface concentrations (i.e., above background) may be obtained with reasonable release rates of ethane (calculations are easily made). It appears quite feasible to rig a tubing network such that samples from 10 locations on the hill surface are continuously pumped past each of 10 FID's. Through a switching network, then, the FIDs are able to repetitively sample each of the 100 locations on a once-per-ten-second basis--conceivably much faster than that--as laboratory studies have rather easily obtained frequency responses of 300 hertz.

(b) Time Resolution Required: To fully understand the physical mechanisms, resolution of concentration fluctuations as well as wind speeds on time scales much shorter than 10 minutes is essential. The necessity for time resolution of the wind fluctuations is obvious. The necessity for resolution of concentrations is not so obvious, but laboratory studies and some large scale field studies have shown that semi-coherent vortex shedding may occur in the lee of hills under strongly stratified conditions. This vortex shedding in the lee causes an oscillation of the plume on the upwind side of the hill, which can markedly reduce surface concentrations. The vortex shedding period is expected to be on the order of a few minutes, so that this physical mechanism would be completely obscured by observing only 10 minute averages. Similarly, any other physical mechanisms taking place on time scales smaller than 10 minutes would be obliterated by 10 minute averages.

(c) Data Feedback and Recording: The above discussion points towards 10 second averages at each of 100 locations for a presumed study period of 3 hours, leading to a total of 100,000 samples/day. This sampling rate and number of samples obviously points to a mini-computer recording on magnetic tape. A system to handle this job would cost under $100K. It can easily be set up to automatically and periodically sample each analyzer, to record each sample on magnetic tape, and to display real-time and/or running-average information at all sampling locations simultaneously. At the end of each study period, all information is immediately available for comparing with models and for user distribution. This system is to be compared with something equivalent to syringe sampling, where a new syringe is filled every 10 minutes at each of 100 locations for a period of 3 hours, yielding 1800 samples that must be individually labeled, handled, analyzed, recorded, flushed, etc., each day. The choice is obvious. A comparable system for wind measurement and recording is likewise in order.

4. Source Configuration and Management: If the vertical width of the plume is too large compared to the hill height, we will be unable to learn much about the flow structure over the hill, because surface concentrations would be essentially uniform. If its vertical width is too small, it will not be possible to resolve the plume structure as it approaches or encounters the hill, e.g., lidar measurements would be unable to resolve the plume as it approaches the hill, and similarly, too many samplers would be required on the hill surface. An appropriate number appears to be $\sigma_z = 10$ to 15 m for a 100 m hill. Such plume widths could be obtained by placing the source an appropriate distance upwind for the existing stability class. From Turner's workbook, indicated distances are 1 km for F-stability and 400 m for D-stability (this is another reason for having a mobile source). An alternative would be to configure the source to obtain the desired initial plume widths, for example, by emitting the tracer through an array of tubes spaced in a rectangular matrix in the y-z plane.

Several Workshop participants expressed the opinion that once the source was fixed and sampling began, the source should not be moved again for the duration of the study period, i.e., 3 hours. I agree with this concept in principle, but, in practice, it may be entirely appropriate to move the source. Suppose, for example, after collecting samples for a one-hour period, there is an obvious and permanent shift in the wind direction of 180°. This could be the case (and possibly, quite predictably) shortly after sunrise if the 100 m hill were located in a broad sloping valley. It seems to me fruitless and wasteful of resources to continue the scenario another two hours; it would be far better to move the source 180° around the hill and begin a new scenario, obtaining useful data. It would be obvious from the wind records, in any event, that the three-hour-average concentration for the first scenario would be one-third the one-hour-average concentration. Of course, strict protocols would be mandatory and decisions would have to be based on prior experience, but a rigid specification of an absolutely fixed source position is too restrictive.

5. Anabatic and Katabatic Winds. The lack of knowledge concerning the nature, strength, and thickness of anabatic and katabatic

winds was apparent at the Workshop, but the general consensus appeared to be that they would be small to insignificant on the 100 m hill, yet predominant on a 500 m hill. Because there are numerous physical mechanisms to be understood before constructing an adequate mathematical model (the nature of the impingement process, the closeness of approach of streamlines to the hill surface, the wind meander factor, anabatic and katabatic winds, etc.), it is logical to eliminate as many variables as possible in order to fully understand the remaining processes. If anabatic and katabatic winds are insignificant on the 100 m hill, it is therefore a logical first step. In any event, a few smoke studies before any equipment is set up would provide very useful knowledge on the existence and nature of any such thermally generated surface winds, so that we may be prepared to quantify them as necessary.

August 9, 1979

Dr. Bruce A. Egan
Environmental Research & Technology, Inc.
3 Milata Drive
Lexington, Massachusetts 02173

Subject: Your memorandum AQC-833 of July 25, 1979, concerning EPA Rough Terrain Workshop

Dear Bruce:

I was away from the office until your deadline for comments so I am sending a copy of this letter to Einar Hovind.

I find no fault with the panel report. It appears to reflect most of the concerns that were expressed at the panel sessions.

Upon reflection and a plotting to scale I am concerned that 100 tracer samplers will not be enough to define the ground level concentration pattern and concentration gradient normal to the hill. For example, an oval hill that peaks at 120 meters with a six to one slope would require 25 samplers at 20 meter spacing along the 60 meter contour level for just one quadrant. The recommendation should be 200 samplers.

The Workshop was enjoyable and I look forward to seeing the report.

Very truly yours,

TRC - THE RESEARCH CORPORATION
of New England

Norman E. Bowne,
Vice President & Chief Scientist

NEB/mfr

cc: Einar L. Hovind
North American Weather Consultants

August 13, 1979

Mr. Einar L. Hovind
Vice President, Air Quality
North American Weather Consultants
600 Norman Firestone Road
Goleta, California 93017

Dear Einar:

I am enclosing a copy of my letter of August 1 to Maynard. Note the circled third paragraph*. If such a distance range is not already covered under the group that waas working on project design, I think it is important to show how difficult it will be to have the tracer "hit the hill" as the release point is moved from two km to four km up wind.

For your general information Gerard DeMarrais telephoned Montana Power last week to inquire as to the availability of the small hill upon which the meteorological tower is located for field experimental work. Unfortunately that hill is not 100 meters high and it is more conical in shape than the 3 to 1 aspect ratio recommended by the Working group of which Maynard Smith was the head.

*"Perhaps an item 8 under the Small Scale effort should indicate a distance range up-wind from the hill be recommended for tracer release. I personally would like to see some data collected at both 2 and 5 km up-wind from the first possible impingement point on the hill. Such an investigation will clearly illustrate the less precise air flow pattern for a greater distance. Perhaps it could be better stated as not less than 2 km up-wind with a second release effort not more than 6 km up-wind."

I appreciate the opportunity to join with others at the Workshop in North Carolina. However, I remain unconvinced that the findings of a detailed study project using a hill in the center of a valley will answer the real life problems of the imagined impingement on the shoulder terrain many kilometerss away from a power plant in the center of the valley.

Sincerely yours,

Loren W. Crow, CCM

LWC:dd
Enc.